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Journal of Experimental Psychology

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VOL. XIV, No. 4 AUGUST, 1931

ELEVATION OF THE EYE-BALLS ON WINKING

BY W. R. MILES

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HISTORICAL

It is a matter of surprise that the remarkable essay by Sir Charles Bell, "On the Motions of the Eyes, etc." read before the Royal Society, March 20, 1823, (1) should be so infrequently given as a reference in ophthalmological and psychological writings. The self-observation recorded in this account is one of the finest bits that has been contributed toward the understanding of the motor functions of the eye. Bell discovered that the eye-ball itself has a characteristic upward motion at the time of winking which serves important purposes in the visual economy. He discusses these matters at length and formulates a theory of nervous control of the different eye muscles. The eminent writers on visual function since his time have usually given no notice to the matter of lateral eye movements at lid closure or they have dismissed the topic as unimportant and without citing Bell's essay. A noteworthy exception to this rule is Savage (2) published 1906.

It is common enough for writers on the eye and nervous system to mention ' Bell's paralysis ' or ' Bell's phenomenon ' in connection with pathological conditions of the facial nerves. They refer to the ' well-known ' upward roll of the eye-ball during sleep or in anæsthesia and describe the upward movements of the cornea exhibited when an individual having

paralysis of the facial muscles tries to wink, or to voluntarily close the eye. Almost invariably they describe this eye-ball movement as a rather elaborate alternate method of moistening and cleaning the cornea which the patient adopts when and after he can not properly move his eye-lids. One practically never finds in these discussions any hint that Bell discovered these corneal motions as normal for persons with normal face muscles and nerves. It is an uninvestigated field.

Since Bell's essay is evidently so little known I shall not attempt to re-describe what he found and what he says but will let him say it in his own lucid paragraphs.[1]

Charles Bell's Observations

Bell begins his discussion as follows:

"The object of this paper is to explain the reason of there being six nerves distributed to the eye, and consequently crowded into the narrow space of the orbit.

"But before it is possible to assign the uses of these nerves, we must examine the motions of the eye more minutely than has hitherto been done, and try to comprehend the offices to be performed. Much as the eye has been studied, the framework which suspends it, and by which it is moved and protected, has not received the attention it deserves. . . ."

"It is, therefore, necessary to divide the paper into two parts. *First*, to show the uses of the apparatus which is exterior to the eye-ball; and then, in the *second place*, to consider how the nerves minister to these offices." p. 166.

"I propose to show, that we must distinguish the motions of the eye, according to their objects or uses, whether for the direct purpose of vision, or for the preservation of the organ: that the eye undergoes a revolving motion not hitherto noticed; that it is subject to a state of rest and activity, and that the different conditions of the retina are accompanied by appropriate conditions of the surrounding muscles;

[1] Bell's paper has the title, "On the Motions of the Eye, in Illustration of the Uses of the Muscles and Nerves of the Orbit." By Charles Bell, Esq. Communicated by Sir Humphry Davy, Bart. P.R.S. Philosophical Transactions of the Royal Society of London, Part I, 1823, pages 166–186. A plate containing two excellent engravings accompanies this article; Fig. 1, the muscles of the eye seen in front; Fig. 2, the muscles of the eye seen in profile. Special attention is given to the oblique muscles. Both figures are lettered and appropriate legends are given. The essay is reprinted with citation of the original place of publication in 'An exposition of the natural system of the nerves of the human body, with a republication of the papers delivered to the Royal Society, on the subject of the nerves, by Charles Bell, Philadelphia, 1825.' See pages 121–141. Replicas of the original illustrations are included in this reprinting. According to the statement of Savage (2) Bell's essay is also republished as a chapter of Charles Bell, *The Nervous System of the Human Body*, 1830.

that these muscles are to be distinguished into two natural classes; and that in sleep, faintness, and insensibility, the eye-ball is given up to the one, and in watchfulness, and the full exercise of the organ, it is given up to the influence of the other class of muscles: and finally, that the consideration of these natural conditions of the eye explains its changes as symptomatic of disease, or as expressive of passion." p. 167.

"*Motions of the Eye-ball and Eye-lids.*"

"Two objects are attained through the motion of the eye-ball. First, the control and direction of the eye to objects; second, the preservation of the organ itself, either by withdrawing the surface from injury, or by the removal of what is offensive to it. Without keeping this distinction before us, we shall not easily discover the uses of the parts.

"There is a motion of the eye-ball, which, from its rapidity, has escaped observation. At the instant in which the eye-lids are closed, the eye-ball makes a movement which raises the cornea under the upper eye-lid.

"If we fix one eye upon an object, and close the other eye with the finger in such a manner as to feel the convexity of the cornea through the eye-lid, when we shut the eye that is open, we shall feel that the cornea of the other eye is instantly elevated; and that it thus rises and falls in sympathy with the eye that is closed and opened. This change of the position of the eye-ball takes place during the most rapid winking motions of the eye-lids. . . ." p. 168.

"The purpose of this rapid insensible motion of the eye-ball will be understood on observing the form of the eye-lids and the place of the lacrymal gland. The margins of the eye-lids are flat, and when they meet, they touch only at their outer edges, so that when closed there is a gutter left between them and the cornea. If the eye-ball were to remain without motion, the margins of the eye-lids would meet in such a manner on the surface of the cornea, that a certain portion would be left untouched, and the eye would have no power of clearing off what obscured the vision, at that principal part of the lucid cornea which is in the very axis of the eye; and if the tears flowed, they would be left accumulated on the center of the cornea, and winking, instead of clearing the eye, would suffuse it. To avoid these effects, and to sweep and clear the surface of the cornea, at the same time the eye-lids are closed, the eye-ball revolves, and the cornea is rapidly elevated under the eye-lid." p. 169.

"By the double motion, the descent of the eye-lid and the ascent of the cornea at the same time, the rapidity with which the eye escapes from injury is encreased. Even creatures which have imperfect eye-lids, as fishes, by possessing this rapid revolving motion of the eye, avoid injury and clear off impurities.

"I may observe in passing, that there is a provision for the (p. 169) preservation of the eye, in the manner in which the eye-lids close, which has not been noticed; while the upper eye-lid falls, the lower eye-lid is moved towards the nose. This is a part of that curious provision for collecting offensive particles towards the inner corner of the eye. If the edges of the eye-lids be marked with black spots, it will be seen that when the eye-lids are opened and closed, the spot on the upper eye-lid will descend and rise perpendicularly, while the spot on the lower eye-lid will play horizontally like a shuttle." p. 170.

Bell then discusses the third eye-lid in quadrupeds, and its still more perfect form in birds. In reference to the human eye some paragraphs later he continues:

"There is another division of this subject no less curious; the different conditions of the eye during the waking and sleeping state, remain to be considered. If we approach a person in disturbed sleep when the eye-lids are a little apart (p. 171), we shall not see the pupil nor the dark part of the eye, as we should were he awake, for the cornea is turned upwards under the upper eye-lid. If a person be fainting, as insensibility comes over him the eyes cease to have speculation; that is, they want direction, and are vacant, and presently the white part of the eye is disclosed by the revolving of the eye-ball upwards. So it is on the approach of death; for, although the eye-lids be open, the pupils are in part hid, being turned up with a seeming agony, which however is the mark of encreasing insensibility." p. 172.

Several paragraphs later this keen observer makes the following statement:

"In the violent spasmodic affection of the eye, when it is painfully irritated, I believe that all the muscles, both of the eye-ball and eye-lids, are excited." p. 176.

Again in reference to winking he says:

"From these experiments it is proved, that the division of the oblique muscles does not in any degree affect the voluntary motions by which the eye is directed to objects. p. 176. This cannot however be said of the involuntary winking motions of the eyes. We have seen that in winking to avoid injury, the oblique muscles were in operation; and that the inferior oblique muscle gained in the power of elevating the eye-ball by the division of the superior oblique, its opponent." p. 177.

"*On the Two Conditions of the Eye, its State of Rest, and of Activity*"

"The eye is subject to two conditions: a state of rest with entire oblivion of sensation, and a state of watchfulness, during which both the optic nerve and the nerve of voluntary motion are in activity. When the eye is at rest, as in sleep, or even when the eye-lids are shut, the sensations on the retina being then neglected, the voluntary muscles resign their office, and the involuntary muscles draw the pupil under the upper eye-lid. This is the condition of the organ during perfect repose. p. 177.

"On the other hand, there is an inseparable connection between the exercise of the sense of vision and the exercise of the voluntary muscles of the eye. When an object is seen, we enjoy two senses; there is an impression upon the retina; but we receive also the idea of position or relation, which it is not the office of the retina to give. . . ."

"Let the eye be fixed upon an illuminated object until the retina be fatigued, and in some measure exhausted by the image, then closing the eyes, the figure of the object will continue present to them: and it is quite clear that nothing can change the place of this impression on the retina. But notwithstanding that the impression on the retina cannot be changed, the idea thence arising may. For by an exertion of the voluntary muscles of the eye-ball, the body seen will appear to change its place, and it will, to our feeling, assume different positions according to the muscle which is exercised. If we raise the pupil, we shall see the body elevated, or if we depress the pupil, we shall see the body placed below us; and all this takes place while the eye-lids are shut, and when no new impression is conveyed to the retina. The state of the retina is here associated with a consciousness of muscular exertion; and it shows that vision in its extended sense is a compound operation, the idea of position of an object having relation to the activity of the muscles.

"We may also show, by varying this experiment, that an agitated state of the muscles, or a state of action where the muscles are at variance or confused, affects the idea of the (p. 178) image. If we look on the luminous body so as to make this impression on the retina, and then cover the face so as to exclude the light, keeping the eye-lids open, and if we now squint, or distort the eyes, the image which was visibly impressed upon the retina instantly disappears as if it were wiped out. Does not this circumstance take place, because the condition of the muscles thus unnaturally produced, being incongruous with the exercise of the retina, disturbs its operation?

"If we move the eye by the voluntary muscles, while this impression continues on the retina, we shall have the motion of place or relation raised in mind; but if the motion of the eye-ball be produced by any other cause, by the involuntary muscles, or by pressure from without, we shall have no corresponding change of sensation.

"If we make the impression on the retina in the manner described, and shut the eyes, the image will not be elevated, although the pupils be actually raised, as it is their condition to be when the eyes are shut, because there is here no sense of voluntary exertion. If we sit at some distance from a lamp which has a cover of ground glass, and fix the eye on the center of it, and then shut the eye and contemplate the phantom in the eye; and if, while the image continues to be present of a fine blue color, we press the eye aside with the finger, we shall not move that phantom or image, although the circle of light produced by the pressure of the finger against the eye-ball moves with the motion of the finger.

"May not this be accounted for in this manner: the motion produced in the eye-ball not being performed by the appropriate organs, the voluntary muscles, it conveys no sensation of (p. 179) change to the sensorium, and is not associated with the impression on the retina, so as to affect the idea excited in the mind? It is owing to the same cause that, when looking on the lamp, by pressing one eye, we can make two images, and we can make the one move over the other. But, if we have received the impression on the retina so as to leave the phantom visible when the eye-lids are shut, we cannot, by pressing one eye, produce any such effect. We cannot, by any degree of pressure, make that image appear to move, but the instant that the eye moves by its voluntary muscles, the image changes its place; that is, we produce the two sensations necessary to raise this idea in the mind; we have the sensation on the retina combined with the consciousness or sensation of muscular activity.

"These experiments and this explanation of the effect of the associated action of the voluntary muscles of the eye-ball, appear to me to remove an obscurity in which this subject has been left by the latest writers. . . ." p. 180.

"The Author has to regret that these minute circumstances regarding the action of the muscles of the eye have led him to so great a length; he hopes they are not altogether without interest in themselves, while the discussion will afford him secure ground for establishing an arrangement of the nerves of the eye, and will enable him to distinguish them according to their uses." p. 186.

In a second lecture read before the Royal Society June 19, 1823, Bell discusses the nerves of the orbit. Present day physiologists may disagree with his classification of voluntary and involuntary recti, but when they read his paragraphs they must admit that he did outstanding work on the problem, and psychologists can but freely praise the early in-

geniousness of his self-experiments, as well as his thoroughness and care in interpretation.

Albrecht von Gräfe's Observations

In 1855 von Gräfe (3) published a short contribution on the movements of the eyes from lid closure. He cites two cases that demonstrate in a very clear way the nature of the neuro-muscular arrangement of these reflexes. His observations are as follows:

"It is a generally known fact that the eyes roll upward at the closing of the lids. But this rule seems to have its exceptions. In the case of a boy who was suffering from lagophthalmus as a result of caries of the orbit, and in whom therefore the position of the cornea could be well observed, I noted that whereas the cornea slipped under the palpebra superior at most of the lid closings, it occasionally and especially at forcible shutting showed an opposite motion in which the cornea completely disappeared under the lower lid. Then I noted that although the decided movement of the cornea (at lid closure) was obviously to be ascribed to a synergistic contraction of the muscles in question with the orbicularis, the latter contributed directly to this anomaly. I became convinced of this in a case of paralysis of all the eye muscles. After a chill a woman, otherwise healthy, had a ptosis of the left eye and experienced complete immobility of the eye. At the examination a paralysis of all the branches of the oculo-motor and the abducens nerves appeared, and incomplete paralysis of the trochlear nerve. There was still some abduction and downward rolling motion in the effort to look upward. Finally there was a very definite weakening of vision, which could not be attributed to the moderate dilation of the pupil, and paralysis of accommodation, but which indicated the necessity of assuming a pathological condition of the optic nerve, the more so as all changes in the refracting media and inner mechanism were missing at the ophthalmological examination. It was quite striking to me that the immovable cornea which did not move in the least in an effort to glance upward went through an elevating movement whenever the patient closed her eyes or blinked. The eye which was before absolutely fixed now suddenly appeared mobile. I could attribute this motion only to the pushing and lifting of the lower lid for, when I drew the latter aside toward the cheek and from the bulb of the eye, and now let the patient close her eyes, not the least movement occurred, but it did occur again as soon as the lower lid touched the eye again, that is, when the pressure was relaxed. As a matter of fact, the lower lid in fitting so closely to the convexity of the eye, can dislocate it upward and also against the fatty lining of the orbit. Whether in a normal state there actually occurred under these conditions a change in the axis of rotation, or whether perhaps the push of the orbicularis acts as a stimulus in such a way upon the eye muscles that a rolling of the cornea toward the opposite side occurs, which is similar to that caused by touching the eye with an instrument and thereby causing a blinking movement of the cornea,—this I cannot determine."

The above is the complete content of von Gräfe's note on the subject. It is the most detailed analytical account of these coördinations that I have been able to find aside

from that of Bell. The two original contributions have been quoted at length because of their own intrinsic interest and to assist in bringing them into relation with future experimental work that may be done on the subject.

Experimental Results

The first eye movement records that gave the writer a clear indication that the eye-balls sometimes turned upward at the moment of waking were those taken in connection with the eye reaction measurement. Photographing was done from the corneal reflection after the method of Dodge, and recorded on a falling plate. The subject viewed a fixation mark which suddenly disappeared, and at that moment the recording beam of light was turned on his eye and a new mark was presented in the peripheral field. He directed his eye to this new mark as quickly as possible and held it there for about four seconds. The first vertical line from the beginning until the bend, made by the reaction movement, represented the reaction time. Following this there was a vertical line of dots which was at times interrupted by the winking of the subject. Winking of course cut off the reflected light from the cornea and thus interrupted the photographic tracing. Sample records of this kind are shown in *A*, *B*, *C*, and *D* of Plate I. These are to be read from the bottom upward. Each dot represents .01 second. We are not, however, interested in the time dots particularly, but in the general configuration of these lines. At several places the lines momentarily terminate in more intense white marks, made evidently by a concentration of the dots on one portion of the photographic emulsion. The only way in which such a concentration in the line can take place is by a vertical movement of the eye, since we are photographing through a lens and the plate is moving down. If the eye moves upward the beam of light reflected from the cornea will be held at a relatively constant position on the plate for a longer period than if the eye is still. Sometimes the line of dots takes up again after the intensified point, and then we see that the dots are stretched out—thinned and made longer,

indicating that for a time the eye was moving downward, opposite to the direction of the moving plate, therefore, the plate got a shorter amount of exposure. The writer began to take note of such records in 1914, and doubtless other investigators in the field of eye movements before that date must have noticed these oddities in some of their tracings.

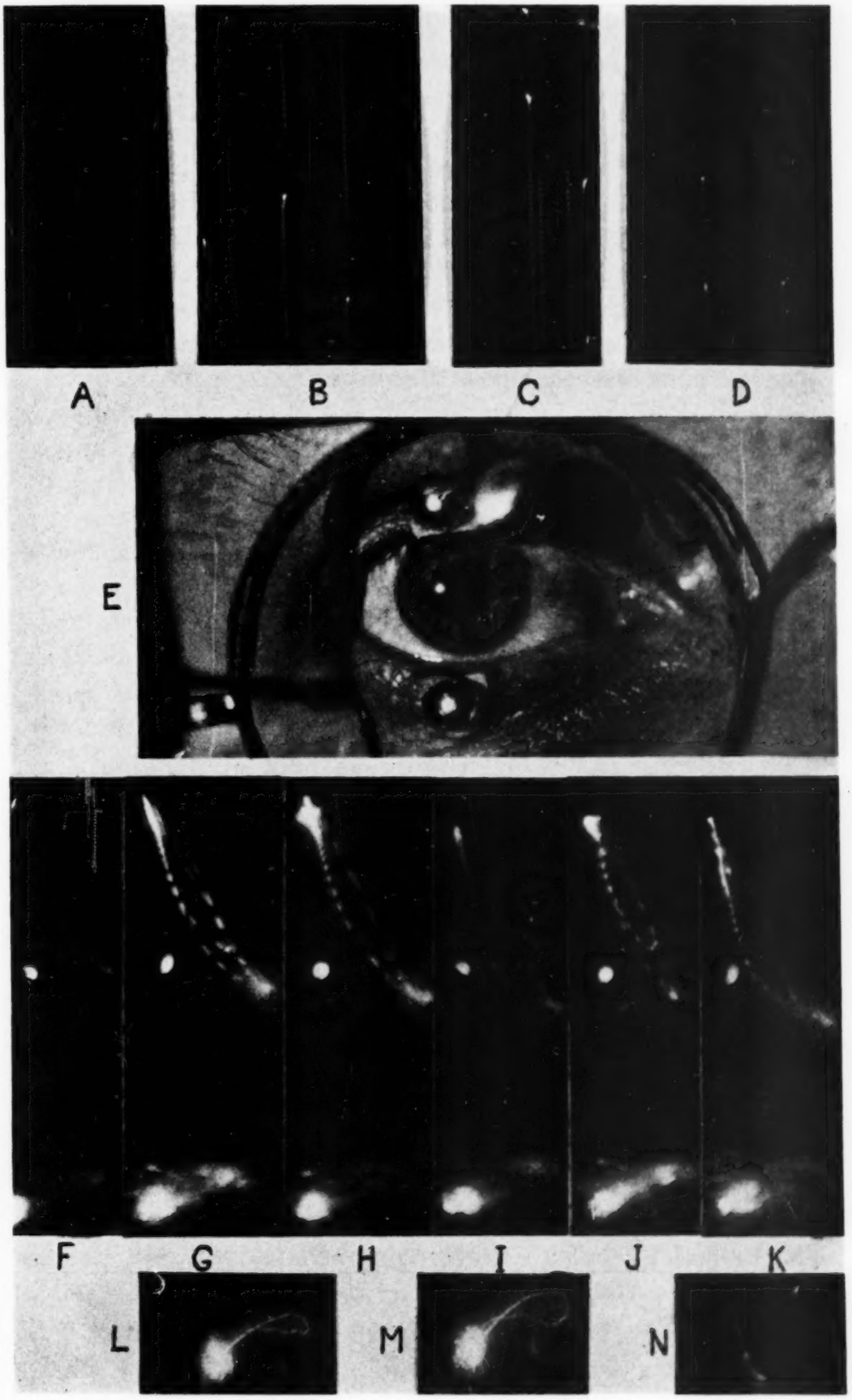
The first entry in the way of an experimental protocol that I have on this subject is dated May 27, 1924, 9:00 P.M. In looking at a remote exit light, while the hall was largely dark, it was noticed that on closing the eyes the light regularly appeared to flash downward, exhibiting a short 'comet-tail appearance' below itself. This was taken to mean that the eye jumped upward, with the closure of the lids. The shortest, slightest winks resulted in scarcely an observable effect, but from leisurely closure there was nearly always a fairly long trail. It was noted that the trail was not always vertical. It sometimes curved to the right or to the left, and this did not seem to depend regularly upon the position of the head. It was not possible to notice the light trail on opening the eyes, but only on closure. The results were practically the same for binocular or monocular closure.

This type of self-observation was repeated on several subsequent occasions, and Carr's (4) study on the visual illusion of motion during eye closure was read in this connection. Carr takes up the hypothesis of forward and backward displacement of the bulb within the socket due to lid closure, but not elevation of the eye-ball. At this stage the writer was not familiar with the essay by Bell or the note by von

---

PLATE I. Arrangements for recording and records of the movements of the lids and the eye-ball on winking. *A*, *B*, *C* and *D*, portions of eye reaction records which incidentally show elevation of the eye-ball at winking. *E*, photograph of a subject's right eye with mirrors attached to the lids. *F*, *G*, *H*, *I*, *J* and *K*, wink records for the right eye taken on stationary film. The paths of movement for the upper lid are quite clearly shown. Closure is much more rapid than opening. Each dot in the line of movement equals .01 sec. The direction of movement of the cornea is indicated by the elliptical shape of the reflected dot. *F*, *G*, *H*, *I*, *J* and *K*, indicate more movement nasalward than upward by the lower lid. *L* and *M*, records for lower lid movement. *N*, fragment of record showing the opposed axes of motion for upper lid and cornea; both move toward the nose, one down and the other up.

PLATE I.



Gräfe, and he naïvely believed he had discovered a hitherto unknown feature of the wink coördination.

The next step was to arrange for photographing this synergism of movement. The arrangements for recording are simple ones as shown in photograph *E* of Plate I. This reveals the right eye of a subject enlarged about two times. Small spherical mirrors were attached to the tarsal edges of both eye-lids at points midway of the lids and vertical in reference to each other when the eye was open. An arc lamp with the beam interrupted one hundred times per second was placed some distance from the subject's eye. The corneal reflection is shown just at the left hand edge of the subject's pupil in picture *E*, and larger reflections of the arc appear in both curved mirrors, attached to the lids. These tiny mirrors were mounted on bits of pith attached to the eye-lids by the use of a little gum arabic. The mirrors, including attachment each weighed 0.15 gm, and produced absolutely no irritation to the cornea or to the lid. They could be worn for hours without the slightest inconvenience. A subject quite forgot them in between periods of photographing, unless he unconsciously rubbed the hand across the face and dislodged them. A spectacle frame carrying a bright bead for registering the head line is also indicated in photograph *E*. It was found possible to hold the head sufficiently still and thus to dispense with this open spectacle frame. In some cases the contour of the upper lid was such that the mirror folded back well under the brow, so that at the very beginning of winking the registration of the line for the upper mirror does not show.

All of the records illustrated and discussed in this paper are from lid closures (winking) such as one would normally have during the process of reading or of looking at a picture. No sound, flash, rapid approach, electric shock, or puff of air stimuli were employed. The bright light used in recording was something of a natural stimulus to cause winking. The subject fixated a certain point and periodically felt the natural corneal urge to wink. At other times he was asked to keep his eye on the fixation point and wink rapidly.

The first recordings were on stationary 5 × 7 inch films with a magnification of five times. A group of six such records are shown in Plate I, see *F*, *G*, *H*, *I*, *J*, and *K*. The most conspicuous thing in these and other such records is the prominent diagonal components of movement demonstrated both by upper lid and lower lid. The path of the lower lid is not clearly indicated, but the blur shows the approximate course of contraction and return. A given point near the center of the tarsal edge of the lower lid moves about twice as far toward the nose as it moves in the vertical direction. A more precise outline of the path, verifying the previous statement, is shown in the portion of a record reproduced in Plate I. These records are confirmatory of Bell's description of the lower lid movement. The upper lid moves nasalward one-half to three-fifths as far as it moves downward. Bell reports it as moving vertically but this can hardly be correct as both of these movements are the natural mechanical result of the sphincter action of the orbicularis.

In each of the six records illustrated the position of the cornea of the eye-ball is represented by the white dot fairly midway of vertical dimension. In no case is this dot round as in photograph *E*. Some of the dots are more elliptical than others, but all of them show stretching out in an axis that is as much up and nasalward as the closure of the upper lid is down and nasalward. These two closure angles appear to be equal in deviation from the vertical and opposed to each other. The two angles are well illustrated in the bit of record reproduced as *N* in Plate I. Here the lower excursion of the upper lid, the longer line at the left in the figure, is shown, while the record for the cornea is stretched out in an axis reaching towards the upper right.

Plate II illustrates several wink coördinations taken on film moving horizontally to the left at the rate of 2 cm per second. These records vindicate the synergistic nature of the movements of the lids and eye-ball at the time of closure. Of course, it nearly always happens that the very apex of the curve inscribed by the corneal movement is missing, because the upper lid, coming down over the cornea, interrupts

the recording. The approximate outline of the curve is, however, suggested by the initial first upward turn of the corneal line and the more prolonged downward turn of the line after winking as fixation is again reëstablished. Very occasionally there was a small movement of the lid, which did not entirely cut off the view of the cornea. (See the central record in *P* of Plate II.) Here the complete curve for the eye-ball movement is exhibited. The elevation of the cornea in this case was probably of slighter amount than that for the preceding wink at the left, or the succeeding voluntary and sustained closure of the lid, at the right. But there is good reason to believe that the general form of the elevation movement corresponds closely in all three cases.

The records of corneal movement exhibited in *O*, *P*, *Q*, *R*, *S* of Plate II in every case show a quick upward turn of the pupil at the moment of the downward stroke of the upper lid. The exact temporal relationship of these events is not exhibited as no signal has been introduced into the time line. The time dots in the record are somewhat stretched out to the right, at the upward shift of the cornea, indicating the diagonal nasalward character of the movement.

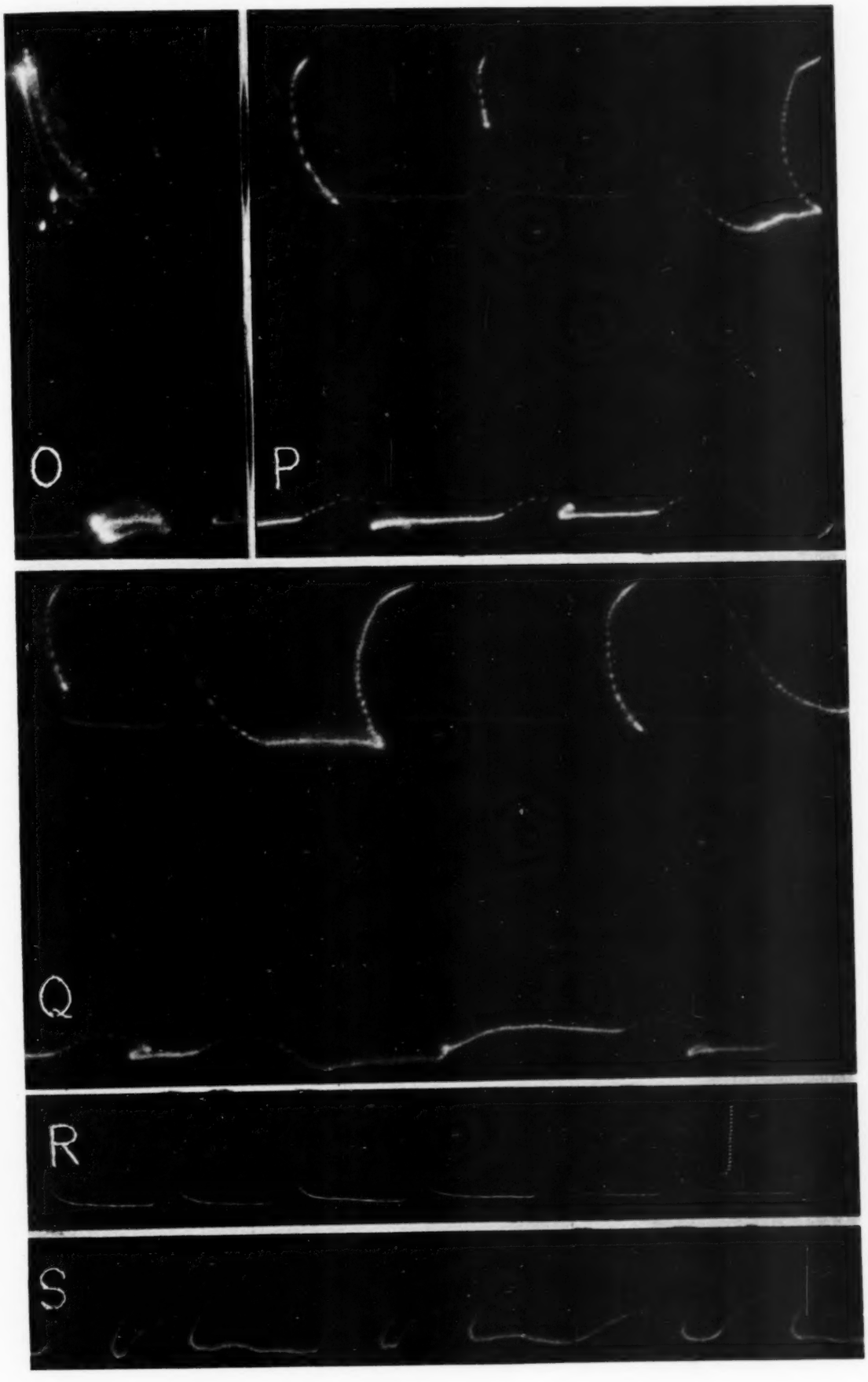
Close examination of the records and measurement of the time dots indicate that the upward movement of the cornea occupies usually about .05 sec while the downward movement occupies about .11 sec. The elevation of the eye-ball appears to be accomplished in a shorter time than is required for the complete lowering of the upper lid. As a response the corneal elevation may be set off by the movement of the upper lid, or it may be a mechanical effect from the contraction of the lower lid. We cannot answer these questions at present.

PLATE II. Illustrative records of synergetic eye winks on moving film. Records from right eye with film moving from right to left at the rate of 2 cm per second. The dots which make up the record lines are each of the value of .01 sec.

In record *O*, just before the film was set in motion several winks occurred which are shown not to have taken the same paths. *P*, section of record showing in order from left to right, an ordinary wink, a very slight wink and a prolonged voluntary closure. The path of corneal movement at the slight wink is fully revealed.

Q, record showing regular winks alternating with prolonged closures. *R*, the corneal record for several successive rapid winks. The lowering of the cornea is seen to be much slower than its elevation. *S*, rapid winking of the lower lid; fantastic by reason of unusual placement of the recording mirror.

PLATE II.



On the records illustrated in Plate II a vertical distance of 1.3 mm equals 40° on the arc of vision. The elevation of the cornea is shown on the records to range from 3 to 5 mm of vertical displacement, which would equal from 10 to 15 degrees of angular movement. The covering of this distance in .05 sec corresponds very closely to the saccadic angular velocity as found by Dodge (**5**) for 15° horizontal movements. But in this case we cannot think of the movement as a typical saccadic displacement in the line of regard. The usual wink to refresh the condition of the cornea, and probably also to enliven the state of the retina, requires .25 sec. By the end of this period the subject has again taken up the same fixation position from which he started. By the end of .15 sec the eye has returned to within 2 or 3 degrees of the original fixation level. The lower half of the wink record, that portion which ordinarily completely obscures the view of the pupil and thus cuts off the retina from visual stimulation, is much the shorter half. The contraction takes place at a high rate of speed and shows prompt deceleration. The pause of the eye at the maximum point of contraction is very short, usually not lasting more than .02 sec. From this the acceleration in opening picks up quickly and gets the lid above the normal line of sight in something like .06 sec. When once above this position the lid settles back into its relaxed state in a leisurely manner. This lower half of the wink, the actual visual cut-out period, is for an interval of about .10 sec.

Visual Fixation After Winking

The eye in renewing its fixation after a wink does not show a corrective saccadic movement, as is typical when the wide-open eye explores for given fixation marks. Evidently the situation following a wink corresponds closely to that during changes in convergence and divergence fixations, where the retina responds to the slowly moving image and adjusts fixation without the use of sharp corrective shifts. This same drifting into the fixation position (or gliding into it) has been noticed in cases of profound sleepiness (**6**), (**7**), when the

saccadic velocity is considerably reduced. These different kinds of evidence relative to fixation of eye movement indicate the following principles of eye coördination:

1. When the eye is at rest it adjusts the shifting of fixation to other specific peripheral points by the initiation of overt saccadic movements of approximately correct amplitude, dependent upon the attitude or attention of the subject.

2. When the eye is in the process of slow movement, whatever the type, occasion or condition that produces the slow movement, it is possible to adjust fixation by the modification of the movement which is in progress.

3. The rate of the continuous movement and the angular displacement of the desired fixation point will determine whether the individual uses overt movement or a modification of the movement in progress to achieve the new fixation position. Taking up fixation after the wink involves no reactive movement of the eye. The curve of depression of the eye is a perfectly smooth, regular one. In this respect the movement for the renewal of fixation is like the beginning of compensatory eye movements (see Dodge's (**5**) Type III), which are adjustments of the eyes to movements of the head.

Associated with the lid closure there is a retraction of the eye-ball which, unless it is directly backward, must slightly displace the cornea in our photographic tracings. The movement for the renewal of fixation is an adjustment for renewed convergence and for both of the displacements which have happened synergistically with the contraction of the orbicularis, and the relaxation of the levator. The elevation of the cornea is the chief element recorded in our illustrated photographic records.

Just how adequate vision is for prearranged fixation points in the first one-tenth second following the uncovering of the pupil after winking I have not determined. Of course, in most circumstances, particularly in the use of the eyes in reading, even though the individual has his effective vision cut low for that duration, this would not constitute a troublesome gap in perceptual experience. But there are other circumstances where winking just prior to some change in

the stimulus material does place the individual at a considerable disadvantage. The change may be objective solely, or it may be a change in the subject's motor coördination in reference to the stimulus, as for example, in aiming and shooting at a target. Here an individual is at a disadvantage if he has to wink just prior to pulling the trigger. The person who can maintain a steady unwinking fixation of his associate's eyes has, if this behavior is not overdone, an advantage n carrying his point. One recalls the well-known remark in Pliny's Natural History (**8**), "The emperor Caius had twenty pairs of gladiators in his training school, and of all these there were only two who did not wink the eyes when a menacing gesture was made close to them. Hence it was that these men were invincible."

The frequency of Bell's wink phenomenon cannot be made out clearly from the data on hand. No record that I have taken in this study exhibits a stationary eye-ball at the time of lid movement. Under conditions of wholly subjective observation, as when looking at a distant light and winking the eyes, one seems to experience occasions when the movement of the eye-balls is very slight or absent, but there is no way of checking these observations. Records *A*, *B*, *C*, and *D* in Plate I do exhibit some terminations of eye reaction tracings which leave off without the indication of a vertical upward movement of the cornea. However, these records cannot be fully trusted because they were taken without proper control in reference to this feature. Recording winks was wholly incidental and I am sure that in some cases the cut-off of the line has been made by the experimenter pulling up the screen and thus interrupting the beam of light from the subject's eye. This was done preparatory to lifting and laterally shifting the plate for recording the next eye reaction record. It certainly is true that the wink is variable in extent and form of contraction. In some of the records on stationary film it will be noticed that before the camera could be closed, the subject had executed two winks. The paths in such cases are not identical. I am not prepared to say that there is always an upward, nasalward movement of the

eye-ball associated with every amplitude and every condition of lid wink or closure; still it does seem that there is typically a movement of the bulb synergic with the movement of the lid, and that usually the corneal movement is upward and nasalward. Our results, therefore, thus agree and verify the self-observations of Bell.

Demonstration of the Synergetic Eye Wink

Pierce (**9**) in his discussion of apparent movements in the Zöllner diagram says, "it can readily be shown that slight closings or openings of the eyes are accompanied by slight upward and downward movements respectively of the eye-ball." He does not suggest any special means of demonstrating this. The writer has found it convenient to show the eye wink to classes and individual students by use of a small Neon light as fixation point (**10**). When this bulb is steadily fixated the luminous filament seems to be perfectly still and glowing as a red-hot iron. The slightest movement of the fixation point or of the eye produces the appearance of vibrating, and large movements of the lamp or of the eye show trails of spots of light.[2] If only one side of the element is in view, 60 flashes of light will be given per second on supplying the light with 60-cycle current. If both sides of the element are in view, there will be 120 flashes of light per second. A short line of such dots extending away from the center of the fovea is much easier to detect in visual perception than is the ordinary continuous line made by moving a candle flame, or some similar stimulus. When the visual field is a varied one and has in it points of high-light, every large eye movement (unaccompanied by wink) distributes these continuous streaks or bands of illumination across the retina. This is such a constant and nonuseful feature of visual experience that as a rule it fails entirely to challenge our attention. Not so with the line of flashes as witness the great success of the Neon advertising sign.

In some experimentation using the Neon glower as a fixa-

[2] Of course, this in principle is the Lamansky (**11**) method. He used perforations in a revolving disk to provide the interrupted pencil of light. The Neon bulb is more convenient and provides a more challenging effect.

tion point I examined 75 university students testing them in groups of five. They were uninstructed in reference to positive after-image and ' fire-brand ' phenomena. The Neon glower was given a short horizontal movement at right angles to the line of vision. They were asked to describe what they had seen. All but one mentioned some kind of a line or trail of dots of light. The one used the term ' line ' but did not record the interrupted character of it. Passing from this simply demonstrated case of positive after-image the usual subject can easily notice the difference between intercepting the light with his hand and intercepting it by closing the eye-lids. He will then begin to notice that there is a string of dots extending downward from the position of fixation practically every time he bats his eyes. He will be able to estimate the number of these dots, and thus the elevation of the eye-ball. The phenomenon is a fleeting one, and the attention must be favorable, but ordinarily it is not a difficult thing to see. This method of demonstration with binocular direct vision is more sensitive than that of using the blind spot in one eye.[3] Bell's method of feeling the movement by the aid of a finger applied to the closed lid of one eye while the other eye is opened and closed alternately is, in the experience of the writer, the least satisfactory. The lid of the closed eye undergoes a slight twitch with every closure of the open eye, and this twitch is in the opposite direction to the slight movement of the cornea under the lid, therefore it is somewhat difficult of detection.

The upward jerk of the eye-ball on winking produces a very observable effect in connection with viewing the reception screen of a tele-vision outfit. This is made up of a series of fine horizontal lines. These lines are moving at a rapid rate and any quick change in the elevation or depression of the eye serves to accentuate some of the lines. The effect is very noticeable. While the ordinary observer may attribute it to some flaw or discontinuity in the tele-vision reception, this is only another illustration of the habitual tendency

[3] A light is made to fall on the blind spot of one eye. When this eye is closed the light should not appear unless the eye-ball moves.

human beings have to regard their visual experiences as objective changes exterior to themselves.

The upward shift of the eye-ball on winking plays a practical role in our observation of rapidly revolving wheels. Here upon occasion we have momentary impressions of the spokes standing still, see L. Bull (**12**). These impressions come mostly at the time of winking. The wink of the eye at the moment of a flash of lightning serves, by the movement of the bulb, to expand and somewhat multiply the apparent stimulus. The perceptual effect is thus more grand than the photographic record would lead one to expect.

Contribution of the Wink to Vision

Winking plays an important part in visual perception. It provides an opportunity for a new visual deal; adaptation is for the moment interrupted; stimuli are sharpened in outline and intensified in color. The more striking stimuli within the range of the visual field, with every wink, get a new opportunity to claim the attention of the observer. Negative after-images can be retained longer by occasional winking than by steady fixation. Winking which falls naturally between lines of reading fixations reduces the senseless visual blur. Finally, fluttering the curtains of the eye is one of the efficient ways of keeping awake and visually active.

Bell gives ' the purpose of this rapid insensible motion of the eye ' as four-fold. (*a*) A stationary eye-ball would not be well served by the eye-lids that we have, because their edges do not touch completely together; therefore certain portions would be left untouched. (*b*) The untouched area would be a place for the deposit of tear fluid and dust directly across the center of the cornea, so that winking in place of carrying this away would suffuse it. (*c*) The double motion, descent of the eye-lid and ascent of the cornea, greatly increases the rapidity with which the eye escapes from injury. (*d*) The double motion facilitates the discharge of fluid from the lacrymal ducts. The writer ventures to suggest some other points not mentioned by Bell, which may be served by this double motion of winking. (1) The external recti secure

relaxation from strain of convergence and fixation; the corollary of this is a renewal of the sensitiveness of the muscles to changes in tension and in their response to visual cues. (2) More complete darkening and thus resting of the retina is secured with the result of renewing somewhat its sensitiveness to stimuli, and of reducing the effects of visual adaptation. (3) Winking serves for a general massage of the eye, promoting venous circulation. (4) By double motion winking the eye avoids constantly pausing the tightly-fitting tarsal edges of the lids at points on the apex of the cornea. This last consideration is quite an important thing to avoid. It is easy to notice that if an individual views a landscape or a picture through half-closed lids for twenty or thirty seconds, when he opens his eyes he will bat them several times in succession. The reason for this, as shown by G. J. Bull (**13**), is that the tightly fitting lid distorts the curve of the cornea. The rapid winking after such distortion is for the purpose of erasing or ironing it out. If the individual always winked with a stationary eye, looking straight ahead, and with the lids coming together just across the apex of the cornea, a mechanical distortion would certainly occur at that point. Similarly, if the individual slept all night, with the eyes looking straight out the lids closed and their borders coming together at the apex of the cornea, on waking the distortion would be so marked as to cause distressing vertical doubling of all objects. Judged on the basis of these several considerations, it is evident that this upward lift of the eye in ordinary winking observed by Sir Charles Bell performs a very important service in the moment-by-moment visual existence of man.

Summary

1. Sir Charles Bell in a paper published in 1823 records having observed that at the time of winking the eye-ball executes a quick upward-turning movement. He stated that this movement could be felt by the finger through the closed lid of one eye while the other eye was opened and closed. He did not describe visual perceptions produced by this eye movement, but gave what he regarded as the purposes

achieved by the double movement of cornea and lids. Bell's paragraphs are quoted.

2. Since the time of Bell, the subject has been practically neglected. The upward roll of the eye in sleep and in anæsthesia has been noted frequently enough but the quick deviation upward and back during winking has been seen only in cases of facial paralysis, and there considered as a substitute for winking.

3. The experimental results given in this paper are for photographic records of winking. Small spherical mirrors were attached to both eye-lids. Photographs taken from in front show the paths of movement for both lids and for the eye-ball which records by means of corneal reflection.

4. At winking the cornea moves upward from 10° to 15°. The upward movement is accomplished in about .05 second and the return downward in .11 second or longer. The corneal movement appears to be accomplished in rather less time than is required for the complete lid movement.

5. The renewal of fixation after winking is by a slow downward drift of the eye-ball not by a saccadic corrective movement. The principles of eye coördination in taking fixation points are presented. A means of demonstrating the synergetic eye wink with the use of a Neon glower as fixation point is described.

6. The upward jerk of the eye-ball at winking avoids having injury done to the curve and shape of the cornea by the tightly fitting tarsal edges of the lids. This and other important visual services are achieved by the eye-ball's taking part in the winking

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THE INTELLIGENCE QUOTIENT AS A FACTOR IN THE WHOLE-PART PROBLEM

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Introduction

The conflicting experimental data on the whole-part problem have suggested with a high degree of probability that the relative efficiency of the whole and part methods of learning is a function of a number of variable experimental conditions, such as method of measuring learning efficiency, material, subjects, type of part method used, and practice. As a consequence, some of the later investigators have arranged their experiments so as to test systematically the possible influence of some such factor. A few studies have indicated that the intelligence of the subject is a factor in the relative value of the two methods.

In 1902, Larguier des Bancels [1] suggested, on the basis of results of poetry learning by one subject with a poor memory and weak attention: "Il est possible que, chez un sujet, incapable de saisir facilement un ensemble d'une certaine importance, la méthode globale perde sa supériorité."

In Neumann's study,[2] published in 1907, the whole method was consistently superior to the pure part with 5 nine- and ten-year old subjects in the learning and retention of 7 French-German pairs, and with 1 nine-year old subject with 8 Latin-German pairs, when reverse association was tested. He concluded from a qualitative analysis of each subject's results that the superiority of the whole method is a function of the general ability and goodness of memory of the subject: "Bei den begabteren und leichter lernenden Vpp. zeigte er (der

[1] J. Larguier des Bancels, Sur les méthodes de mémorisation, *L'Année Psychol.*, 1902, **8**, 201.

[2] G. Neumann, Experimentelle Beiträge zur Lehre von der Ökonomie und Technik des Lernens, *Die experimentelle Pädagogik*, 1907, **4**, 172.

Vorzug der G-Methode) sich sofort deutlich, während bei den schwer lernenden Vpp. erst im Laufe der Übung eine Differenzierung der Lernweisen zu gunsten von G eintrat."

The factor of mental ability was again dealt with by Müller,[3] in 1911, in his experiment on the learning and retention of 4 and 8 lines of poetry, and 8, 10 and 12 nonsense syllables and 8 words by 11 mentally weak subjects, from 11 to 32 years of age, all of whom were subnormal in intelligence and some of whom were suffering from mental disorder. With few exceptions, a part method was superior to the whole in both learning and retention. He concluded that mentally weak subjects, unlike normal individuals, learn better by parts than by wholes.

In 1926, Pechstein[4] published results of 'an original attempt to determine the relation between intelligence levels and learning under the whole-part methodology.' His subjects, 12 eighth grade school children of unstated chronological ages, were divided into two equal groups, a bright group whose I.Q. range was from 125–136, and a dull group with an I.Q. range from 80–93. Each group learned seven different lengths of poetry selections (6, 8, 12, 14, 16, 18 and 21 lines) by four different methods, whole, pure part, progressive part and repetitive part. He drew "two very definite conclusions: 1. Some form of the part method is best for this type of learning. 2. The intelligence quotient is an essential factor in learning, learners of high intelligence being better able to employ the whole method successfully than are learners of lower intelligence levels. The lower the level, the more difficult to learn by the whole method, and the more ineffective it becomes." Pechstein's data are not statistically treated and no individual records are published. An analysis of the average time scores given shows that his two conclusions are unwarranted. Seven comparisons (seven different lengths of material) between the repetitive part method, which

[3] H. Müller, Zur Ökonomie des Lernens bei geistesschwachen Personen, *Sommer's Klin. f. psych. u. nerv. Krankh.*, 1911, 6, 121–157.

[4] L. A. Pechstein, The whole versus part methods in learning: comparison and summary, *Stud. in Educ.* (Yrbk. Natl. Soc. Coll. Teach. Educ., Univ. of Chicago Press), 1926, 15, 181–186.

is the most efficient of the four methods used according to the published tables, and the whole method yield the following results: with the bright group, the repetitive part is superior to the whole in 4 out of 7 comparisons but the average difference between the two methods is ½ percent in favor of the whole; with the dull group, the repetitive part is superior to the whole in 5 out of 7 comparisons, and has an average advantage of 10 percent. It is very doubtful, on the basis of these results, whether there are any reliable differences between the four learning methods *within* each group, much less reliable differences *between* groups.

Sawdon [5] pointed out in 1927 that Winch's data [6] on the learning of four short poems and two long ones by three groups of subjects, 19, 26 and 10 pairs of school children with an average age of 11–6, 12–8 and 13–1 respectively, show that the advantage of the progressive part method decreases with an increase in age, school grade and memorizing ability of the subject. On the basis of this analysis, Sawdon enunciates "the conclusion which Winch hints at but does not definitely formulate, that the greater the mental development the more will the 'whole' method tend to show its value." Although the comparisons upon which this conclusion is based are relatively few, the statistical validity and consistency of Winch's data argue for the probability that 'mental development' (as measured in terms of age, school grade and memorizing ability) is a factor in the relative efficiency of the whole and part methods.

Problem

The present study is an attack upon the problem: Is the relative efficiency of the whole, progressive part and pure part methods in learning and retention a function of the intelligence quotient of the subject? The method employed is that of group comparison. The average scores of a gifted group are compared with the average scores of a normal group

[5] E. W. Sawdon, Should children learn poems in wholes or in parts?, *Forum of Educ.*, 1927, 5, 182–186.

[6] W. H. Winch, Should poems be learnt by school children as 'wholes' or in 'parts'?, *Brit. J. Psychol.*, 1924, 15, 64–79.

in the learning and retention of two types of material with three different methods under the same experimental conditions. The subjects, who were equally divided between the sexes, were school children of chronological ages from 9 yrs., 0 mos. to 10 yrs., 11 mos. The I.Q. of each child was computed on the basis of the Stanford Revision of the Binet-Simon Intelligence Test which had been administered by the writer.

Subjects

The 33 children, 17 girls and 16 boys, who constituted the gifted group were of the mental level which Terman has classified as ' near genius or genius,' *i.e.* I.Q. 140 and above. The mean chronological age of the group was 9–9, and the mean I.Q. 151.2 with a 40 point range, between I.Q. 140 and I.Q. 180. The relatively small number of gifted subjects used is a function of the great infrequency of their occurrence in the child population. The group of gifted children studied by Terman *et al.*,[7] who ranged in age from 2 yrs., 4 mos. to 13 yrs., represented less than one half of one percent (643 out of 159,812) of the juvenile population surveyed for the study, while Hollingworth [8] estimated that children with an I.Q. of over 180 occur perhaps a little more frequently than once in a million. The suggestions made by Terman and Hollingworth concerning the quickest and easiest method of finding gifted children were followed. The survey included private schools and only those public schools in the best residential districts of St. Louis and suburbs where the following children were tested: the child who had made the highest, or almost the highest, score in any group intelligence tests that had been given previously (in over half the schools surveyed no such records were available); the children who were advanced in grade status, particularly the youngest child in the room; the brightest children according to the principal's and teachers' judgments; and those whose fathers were professional men. Utilization was made also of Ter-

[7] L. M. Terman, *et al.*, *Genetic Studies of Genius*, Vol. I, Stanford University, Calif., Stanford Univ. Press, 1925, 19–54.

[8] L. S. Hollingworth, *Gifted Children*, New York, Macmillan, 1926, 42–75; 223.

man's suggestions in reference to an abbreviated scale and order of tests to expedite the elimination of ineligible children. In spite of these short cuts, the search for the gifted group necessitated the individual testing or partial testing of some two hundred children scattered through seven schools,[9] two private and five public schools in St. Louis and suburbs.

The 35 children, 18 boys and 17 girls, who constituted the normal group, were of ' normal or average ' intelligence according to Terman's classification. This group had a mean chronological age of 10–0, and a mean I.Q. of 99.4 with a 10 point range, between I.Q. 95 and I.Q. 105. The writer made a preliminary survey of all nine and ten year old children in the public schools of Fayetteville, Arkansas,[10] with the National Intelligence Tests, on the basis of which the most probably eligible children were selected for individual testing.

Procedure and Learning Materials

The size of the groups used is offset by the approximately individual testing conditions of the experiments and the many records obtained on each child. Each subject learned two samples of each type of material by each of three different methods. Uniformity throughout the study was secured by the writer's conducting all the experiments and marking all the papers. The children were tested in groups, usually of three and never over five, in a separate experimental room. Strict uniformity in place and time of sittings, which always occurred during school hours, and in directions was observed throughout each experiment. All timing was done with a stop-watch. At the beginning of each experiment, the chil-

[9] The writer wishes to acknowledge her indebtedness for their sympathetic and intelligent coöperation to Principal Rossman of the Rossman School, Miss Tillie Bergesch of the Mary Institute, Superintendent John L. Bracken of the Clayton schools, Principal Julia E. Brossard of the Forsythe School, Principal F. G. Roth of the Bellevue School, Superintendent Chas. Banks of the University City schools, Principal Rossi of the Flynn Park School, and Principal O. E. Gordon of the Delmar School.

[10] To Superintendent F. S. Root of the Fayetteville public schools, Principal J. P. Perrill of the Leverette School, Principal J. F. Lawson of the Washington School and Principal Bessie Coventon of the Jefferson School, the writer wishes to acknowledge her indebtedness for their generous coöperation, without which the completion of this study would have been impossible.

dren were instructed in regard to the material to be learned and the procedure to be followed in recall and, on the respective day, the learning method to be employed. These instructions were the same *verbatim* throughout the investigation. Each experiment took eight sittings, which occurred on five school days of one week and the first three of the next. At each sitting (except the first) the sample (poem or list) learned the day before was recalled and then a new sample learned (except at the last sitting). Both learning methods and samples of the types of material were employed in a counter-balanced practice order in Experiments 1, 2 and 3. In the fourth experiment, only the learning methods were so arranged, since a change in the order of the poems would have destroyed their continuity of meaning.

Vocabularies (paired associates) and poems were the materials used. In Experiment 1, 6 lists each having 10 Turkish-English pairs were learned. The Turkish words,[11] which were of one or two syllables, had English equivalents which were likewise of one or two syllables. Each pair, the Turkish word to the left and the English to the right, was printed on a white cardboard, 11″ x 7″, in heavy black letters one inch high. For the purpose of recall, which tested forward association, the Turkish word was printed alone on the reverse side of the card. The order of presentation for recall, which remained the same throughout the experiments, was different from that of learning. Six lists, each of 10 nonsense syllable-English pairs, were used in Experiment 3. The nonsense syllables were a mixture of 0 percent and 6.67 percent association value according to Glaze's classification.[12] Each nonsense syllable, which was printed on the left of the card, was paired with a common English word of one or two syllables. For testing forward association in recall, the nonsense syllable was printed alone on the reverse side of the card.

Short poems of 12 lines constituted the learning material in Experiments 2 and 4. The first four poems used in Experi-

[11] W. S. Foster and M. A. Tinker, *Notes for Instructors* to accompany *Experiments in Psychology* (revised edition), New York, Henry Holt and Co., 1929.

[12] J. A. Glaze, The association value of nonsense syllables, *Ped. Sem. & J. Genet. Psychol.*, 1928, 35, 255–267.

ment 2 were adaptations from William Cullen Bryant's "An Autumn Walk." After making a few changes in the wording to secure simplicity, this poem yielded four units each of which had 12 lines, three verses of four lines each, and the same rhyme scheme and meter. The last two poems in the second experiment, and the six poems in the fourth experiment were taken from another long poem, "A Life Time," by Bryant. They were of the same length, verse formation and rhyme scheme as the first four poems, and similar in meter. Each subject was given the poem, typed according to the learning method, on sheets of white paper $5\frac{1}{2}'' \times 8\frac{1}{2}''$.

With the vocabulary material, in all three methods of learning, each pair of words was given ten repetitions. A presentation of a pair consisted in subjects' and experimenter's spelling out aloud together at a uniform rate the first or foreign word and then pronouncing the English equivalent. The cards were held in plain view of the children who were seated very near the experimenter. After each pair in the list had been repeated ten times, the cards were turned over and the foreign words were presented alone in a different order from that of learning. The subjects wrote the foreign words on sheets of paper, which had been previously numbered, and then the English equivalent if they could. Twenty seconds were allowed for recalling each English word, and two minutes more, after the last foreign word had been presented, for additions or changes. The time allotted was sufficient for the children to recall all they thought they could at the time since very few kept their papers the full two minutes at the end. The following three learning methods were used with the vocabulary material: the *whole method*, in which each pair was presented once in its regular order from one to ten, and this procedure was repeated ten times; a *pure part method*, in which each pair was presented ten times in succession before the next pair was shown; and a form of the *progressive part method*, in which the pairs were presented in groups of two, with one review presentation of all the pairs that had been shown before, after each new group of two was added—the first, second, third, fourth and

fifth groups were given six, six, seven, eight and nine successive repetitions respectively.

With the poetry material, six minutes were given in all three methods for the learning of each poem. At the end of that time the papers on which the poetry was typed were collected and the subjects immediately wrote what they could remember on sheets of paper on which blank lines had been numbered from one to twelve. Most of the children finished before the allotted time of 15 minutes was up, and those who kept their papers the full time were sure they could not remember more and were very willing to hand their papers in. The following three learning methods were employed: the *whole method*, in which the subject was told to 'read through the whole poem just as many times as' he could in the allotted six minutes; a *pure part method*, in which 20 seconds were given for the reading of each line, typed on a sheet of paper by itself, and finally two minutes in which to review the whole poem which appeared on the last page; and a form of the *progressive part method*, in which one minute was given for the reading of the first verse which appeared on page 1, one minute for the second verse on page 2, one minute for a review of the first and second verses on page 3, one minute for the third verse on page 4, and finally, two minutes to review the whole poem on page 5. In both part methods, the children were instructed to turn the pages on the instant of command, and always to read all the way through whatever was typed on a particular sheet. The experimenter knows that the first instruction was obeyed, and is reasonably sure that the second one was also. Throughout the experiments, these instructions were emphasized in order to secure correspondence between the methods called for and the ones actually employed. The learning methods and technique in this study, unlike those used by Winch [13] and Sawdon,[14] afford an equal amount of time for each line in all three methods used.

[13] W. H. Winch, *op. cit.*

[14] E. W. Sawdon, *op. cit.*

Retention Procedure

In all four experiments, the material learned was again recalled after 24 hours in the same room and under the same experimental conditions as those of immediate recall. In each sitting, the test of retention always preceded the learning of the new material. At the end of the first sitting of each experiment, the experimenter said:

"I am going to ask each one of you to give me your solemn promise that you will not talk about these words (or poems) or even think about them until I tell you the experiment is over. It is more important not to talk or think about them than to know them perfectly. Do you—(asking each child in turn)—promise not to talk about these words (or poems) or even think about them? After the experiment is over, it will be all right to talk about them as much as you want. But until then—remember your promise."

It was then suggested that, if the words (or lines of the poems) should suddenly and spontaneously pop into a child's head, he should immediately think of his promise, and then about something else, such as what he planned to do during recess the next day. If his teacher, or the other children or any member of his family should ask him about the experiment, he should reply that he was learning some words and poems, but that he had promised not to talk about them until the experiment was over.

After these instructions against rehearsal had been given, the subjects were then told that the experimenter would return the next day at the same time and ask them to write all they could remember of the material they had just learned and recalled, and would then give them new material to learn. This was done in order to make the retention conditions of the first sample learned comparable to those of later samples, when the children would know that they were to be tested on the next day. Checking up on how well the promise was being carried out occurred throughout the experiment. On each of the first three days this was done on each child at the beginning of the sitting. From the children's behavior and comments, the writer judges that the promise was rather faithfully lived up to. "I didn't even tell my mother"; "I happened to think about the poem last night in bed, but right away thought that I was going to

play first base to-day"; "the girl who sits behind me asked me what we did, but I told her I couldn't tell and wouldn't tell until it was all over": are typical of many spontaneous remarks made. There is no known practical fool-proof method of preventing rehearsal, but the writer contends that the method employed here is superior to the customary one of *laissez-faire* and trusting to luck that the subjects will not review during the interval. Experimenting with school children leads one to doubt seriously whether conditions free from review ever occur 'just naturally.' It will not be hard for anyone who has worked with gifted children to believe that this group, at least, carried out the promise as faithfully as adult subjects could and would.

Results

The scores of the vocabulary material are in terms of the number of correct English equivalents. If the same English word was written after two foreign words, no credit was given. The poetry scores are in terms of the number of correct lines, without taking account of spelling or punctuation. There are two types of poetry scores: V, or *verbatim* scores, in which every word was correct and the line correctly placed; [15] and S, or sense scores, in which the sense of the line was given but not in the exact words. In the four experiments, each subject's record, from which the mean for the group is computed, is an average of two samples of the material learned in a counter-balanced practice order. All sigmas of the differences between learning methods were computed by the long formula,[16] since the following correlations were obtained: with vocabulary, the mean correlation for learning and retention with the gifted was .52 with a range from .31 to .85, and the mean with the normal group was .37 with a range from .08 to .54; with poetry, the mean for the gifted was .70 with a range from .51 to .84, and the mean of the normal was .37 with a range from .14 to .61. In the following tables,

[15] On the rare occasions when a perfect line was out of place, it was counted under sense scores.

[16] Helen M. Walker, Concerning the standard error of a difference, *J. Educ. Psychol.*, 1929, **20**, 53–61.

every difference which is three or more times the sigma of the difference is starred (*).

Vocabulary Material

Experiment 1: [17] *Turkish-English Pairs*

Learning

Inspection of Table 1 reveals that the whole method is

TABLE 1

Comparison of Methods

(*A*) *Learning*

Group No.	Whole		Part		Whole minus Part		
	Mean	S.D.	Mean	S.D.	Diff.	S.D. of Diff.	P/W
Gifted .....31..	5.06	1.55	2.53	1.27	2.53*	.29	50%
Normal .....32..	2.42	1.32	1.48	.87	.94*	.20	61%
Normal/Gifted.....	48%		58%				
(*B*) *Retention*							
Gifted .....31..	4.12	1.49	2.17	1.36	1.95*	.26	52%
Normal .....32..	1.76	1.21	.78	.74	.98*	.18	44%
Normal/Gifted.....	43%		36%				

superior to the pure-part method in both gifted and normal groups in the learning of 10 Turkish-English pairs. Moreover, this advantage of the whole method in both groups is statistically valid. This result, based on group averages, is substantiated by the fact that a much larger percentage of children in each group found the whole method more efficient (Table 2, Experiment 1). Although the whole method

TABLE 2

Percentage Finding Each Method Superior

	Experiment 1				Experiment 3			
	Learning		Retention		Learning			
	Two Method Comparison				Two Method Comparison		Three Method Comparison	
	Gifted	Normal	Gifted	Normal	Gifted	Normal	Gifted	Normal
Whole.....	97	63	88	73	78	55	34	38
Prog. P.....	..	..	..	..	..	..	47	19
Part.....	3	16	3	6	16	26	0	22
Ties.....	0	21	9	21	6	19	19	21

[17] The four experiments are numbered in the order in which they were gone through.

is superior to the part in the two groups, its advantage is both absolutely and relatively greater with the gifted children. This statement is based on three lines of evidence: (1) the percentage the part method is of the whole is less with the gifted than with the normal group (Table 1); (2) the mean score of the normal group is only 48 percent of that of the gifted with the whole method, but 58 percent with the part; and (3) 34 percent more of the gifted than the normal subjects found the whole method superior (Table 2). It should be borne in mind that the differences upon which these comparisons are based are statistically valid.

After the work on the whole and pure part methods had been completed, a progressive part method was introduced to see if there might not be found a method superior to the whole. Its apparent intermediate position between the whole and part cannot be accepted since practice favored the progressive part method, making a valid comparison between it and the other two methods impossible in Experiment 1.

Retention

Table 1 shows that in the retention of 10 Turkish-English pairs after 24 hours the whole method is reliably superior to the pure part in both gifted and normal groups. This result is substantiated by the percentage of subjects finding each method superior (Table 2, Experiment 1, Retention). The advantage of the whole method in retention with the gifted is absolutely, but not relatively, greater than with the normal subjects, as it was in learning. Two facts indicate this greater relative advantage of the whole with the normal group: (1) the percentage the part is of the whole method is 52 percent with the gifted and only 44 percent with the normal (Table 1); and (2) the mean score of the normal group is a larger percentage of the gifted with the whole method than with the part (43% vs. 36%). This result is explained by a comparison of the two groups in terms of the percentage the retention score is of the learning score: with the gifted children the percentage of retention varies little with the learning method (81% with the part and 85% with the whole

method), whereas with the normal group, the whole method yields a greater percentage of retention than the part (72% vs. 52%)

Experiment 3: Nonsense Syllable-English Pairs Learning

In Experiment 3, since the whole, progressive part and pure part methods were employed in a counter-balanced practice order, and each method had had equal previous practice, valid comparisons can be made between all three learning methods. The lists of nonsense syllable-English pairs used as learning material proved to be more difficult than lists of equal length of Turkish-English pairs employed in the first experiment.

TABLE 3

COMPARISON OF METHODS

(A) Learning

Group	No.	Whole		Prog. Part		Part	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Gifted	32	3.51	1.60	3.60	1.80	2.03	1.24
Normal	31	1.58	.74	1.17	.90	1.09	.92
Normal/Gifted		45%		33%		54%	

(B) Retention

Gifted	32	2.03	1.37	1.68	1.49	1.12	.95
Normal	31	.69	.65	.66	.66	.33	.51
Normal/Gifted		34%		39%		29%	

The mean scores given in Table 3 show that the part method was again inferior to both the whole and progressive part in both groups. With the gifted children there is a slight superiority of the progressive part over the whole, while with the normal group the whole method appears the most efficient of all three methods. Table 4, however, reveals that not all of these differences are reliable. With the normal group, the chances are 99 out of 100 that the whole is superior to both the progressive part and pure part methods,

TABLE 4

DIFFERENCES BETWEEN METHODS

	Learning				Retention			
	Gifted		Normal		Gifted		Normal	
	Diff.	S.D. of Diff.	Diff.	S.D. of Diff.	Diff.	S.D. of Diff.	Diff.	S.D. of Diff.
Whole-Prog. P.....	−.09	.30	.41	.14	.35	.29	.03	.12
Whole-Part.....	1.48*	.27	.49	.18	.91*	.20	.36	.13
Prog. P.-Part.....	1.57*	.26	.08	.22	.56	.24	.33	.13

but the intermediate position of the progressive part is not statistically validated. With the gifted group, the part method is reliably inferior to both the whole and progressive part methods between which there is no reliable difference.

These results, based on mean scores, are substantiated by the fact that (Table 2, Experiment 3), with the gifted children, a larger percentage found the progressive part superior to the whole, but not one subject showed a superiority of the part method, while with the normal children, the percentage finding the whole most efficient is about twice as large as that finding either the progressive part or part method superior. Between the latter two methods there is practically no difference.

Again, as in Experiment 1, the advantage of the whole method over the part is both absolutely and relatively greater with the gifted than with the normal subjects. Its greater relative superiority is shown in: (1) the smaller percentage the part method is of the whole with the gifted (P/W equals 57%) than with the normal (P/W equals 69%); (2) the smaller percentage the mean score of the normal is of the gifted with the whole method than with the part (Table 3); and (3) that 23 percent more of the gifted than of the normal found the whole method superior to the part (Table 2, Experiment 3, Two Method Comparison). The same three lines of evidence indicate a greater relative advantage also of the progressive part over the pure part method with the gifted group.

Retention

In Experiment 3, where the practice factor had been controlled, the progressive part method assumes an apparently intermediate position with both groups in the retention of nonsense syllable-English pairs after 24 hours (Table 3). Table 4, however, shows that this position is not statistically validated. The superiority of the whole over the part method with the gifted group is the only reliable difference, although, with the normal group, the chances are 99 out of 100 that the whole method is superior to the part, and 98 out of 100 that the progressive part is also superior to the part. The advantage of the whole over the part method in both groups, and the superiority of the progressive part over the part with the normal group are seen in the percentages of children finding each method superior which are given in Table 5. As was found in Experiment 1, the advantage of the whole over the part is absolutely greater with the gifted group (Table 4), but relatively greater with the normal subjects, since: (1) the percentage the part is of the whole method is 55 percent with the gifted and only 48 percent with the normal group; and (2) the mean score of the normal group is 34 percent of that of the gifted with the whole and only 29 percent with the part (Table 3). Although these percentage differences are not large, the score differences upon which they are based are all reliable. The same lines of evidence indicate a relatively greater advantage of the progressive part over the part method with the normal group than with the gifted. The same conditions with respect to

TABLE 5

Method	Percentage Finding Each Method Superior					Percentage of Retention	
	Two Method Comparison			Three Method Comparison		Retention/Learning	
	Gifted	Normal		Gifted	Normal	Gifted	Normal
Whole	72	55	..	44	32	58	44
Prog. P.	..	..	55	28	30	47	56
Part	9	13	19	6	6	55	30
Ties	19	32	26	22	32	..	..

percentage of retention are found in this experiment as were found in Experiment 1: with the gifted children there is little difference between the whole and part methods in percentage of retention (Table 5), whereas, with the normal subjects, the percentage of retention is considerably greater with the whole, and likewise greater with the progressive-part method than with the part.

Summary of Results on Vocabulary Learning

1. With two types of vocabulary material, lists of 10 Turkish-English pairs and 10 nonsense syllable-English pairs, the whole method is reliably superior to the pure part method with both gifted and normal groups.

2. With both types of vocabulary, this advantage of the whole method over the pure part is both absolutely and relatively greater with the gifted than with the normal children.

3. With nonsense syllable-English pairs, the gifted show a reliable superiority of the progressive part method over the pure part, but no valid difference between the whole and progressive part methods; while, with the normal group, the whole method is superior to the progressive part, but there is no reliable difference between the two part methods.

4. This advantage of the progressive part over the pure part with nonsense syllable-English pairs is both absolutely and relatively greater with the gifted than with the normal children.

5. The greater relative superiority of the whole and progressive part methods over the pure part with the gifted group demonstrates that the I.Q. is a factor in the relative efficiency of these three learning methods.

Summary of Results on the Retention of Vocabulary

1. In retention of both Turkish-English and nonsense syllable-English pairs after an interval of 24 hours, the whole method is reliably superior to the part in both gifted and normal groups. With the nonsense syllable-English vocabulary the apparent intermediate position of the progressive

part method is not statistically validated with the gifted group, but the chances are 98 out of 100 that it is superior to the part method with the normal subjects.

2. The advantage of both the whole and progressive part methods over the part is relatively greater with the normal children, although absolutely greater with the gifted children.

3. The percentage of retention of both types of vocabulary is approximately the same with the whole and part methods with the gifted, but with the normal subjects there is a considerably greater percentage of retention with the whole method than with the part, and also with the progressive part than with the part method with the nonsense syllable-English pairs.

Poetry Material

Experiment 2: 12 Lines of Poetry

Learning

In Table 6, small differences between the whole and progressive part methods appear in both gifted and normal groups in both *verbatim* and *verbatim* plus sense scores. None of these differences, however, is reliable. The percentages of children finding each method superior present further evidence of the lack of pronounced differences between the two methods.

TABLE 6

Comparison of Methods

	V Scores				V + S Scores			
	Gifted		Normal		Gifted		Normal	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Whole	4.25	2.31	.45	.50	7.08	3.07	1.82	.99
Prog. P.	4.41	2.91	.39	.44	7.56	3.42	1.58	.78
	Diff.	S.D. of Diff.	Diff.	S.D. of Diff.	Diff.	S.D. of Diff.	Diff.	S.D. of Diff.
W. minus Prog. P.	−.16	.39	.06	.10	−.48	.47	.24	.20

After the work on these two methods had been completed, a third, the pure part, was introduced. The relative position

of this method cannot be assigned because of the practice factor in its favor, although, with this advantage, it is superior to both the whole and progressive part in both groups.

Retention

In the retention of 12 lines of poetry after 24 hours, the differences between the whole and progressive part methods in both groups with both types of scores are very small, being less than half a line, and are unreliable as Table 7 shows. This lack of significant differences between the two methods is apparent also in the percentage of subjects finding each method superior. The percentage of retention (Table 7) with

TABLE 7

Group No.	Scores	Whole		Prog. Part		Whole-Prog. P.		Percentage of Retention	
		Mean	S.D.	Mean	S.D.	Diff.	S.D. of D.	W.	Prog. P.
Gifted ...30..	V	3.30	2.53	3.58	3.09	−.28	.38	78	81
	V + S	5.73	3.68	5.88	3.57	−.15	.48	81	78
Normal ..32..	V	.11	.17	.03	.14	.08	.04	24	7
	V + S	.77	1.13	.41	.59	.36	.20	42	26

the gifted group is approximately the same for the two methods with both types of scores, but the normal group shows a tendency to have a greater percentage of retention with the whole method with both types of scores.

Experiment 4: 12 Lines of Poetry

Learning

Valid comparisons can be made between the three methods employed in the fourth experiment, since they were used

TABLE 8

COMPARISON OF METHODS

Group No.	Scores	Whole		Prog. Part		Part	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Gifted .....31....	V	4.80	2.65	4.98	2.50	4.59	2.54
	V + S	8.38	2.65	8.81	2.59	8.18	2.64
Normal .....31....	V	.66	.45	.56	.60	.65	.62
	V + S	2.60	1.18	2.54	1.13	2.64	1.29

in a counter-balanced practice order and had had equal previous practice. The mean *verbatim* scores, as well as the mean composite scores, *verbatim* plus sense scores, in Table 8 show only small differences, all in fractions of a line, between the three methods within each group. The sigmas of the differences computed for the *verbatim* scores were all larger than their differences, while Table 9 shows that there are

TABLE 9

V + S Scores

	Learning				Retention					
	Gifted		Normal		Gifted			Normal		
	Diff.	S.D. of D.	Diff.	S.D. of D.	Means	Diff.	S.D. of D.	Means	Diff.	S.D. of D.
W.-Prog. P.....	−.43	.34	.06	.22	6.80–7.25	−.45	.44	1.13–1.16	−.03	.20
W.-Part.....	.20	.36	−.04	.22	6.80–6.45	.35	.54	1.13– .97	.06	.20
Prog. P.-P.....	.63	.46	−.10	.25	7.25–6.45	.80	.47	1.16– .97	.09	.18

likewise no reliable differences within each group in the composite scores. This lack of significant differences between the three methods is also apparent in the percentage of subjects finding each method superior.

Retention

The results here with the three methods are the same as those in Experiment 2: there are no reliable differences between the whole, progressive part and part methods in either group with either type of score. This result appears in both the mean scores and in the percentage of children finding each method superior. Since both types of scores give the

TABLE 10

Percentage of Retention

	Gifted		Normal	
	V	V + S	V	V + S
Whole.....	85	81	32	43
Prog. P.....	72	82	18	46
Part.....	72	79	15	36

same results, only the data in terms of the mean V + S scores are presented here in Table 9. The percentage of retention (Table 10) with V scores show a tendency for the whole method to be superior to the other two methods in both groups. With the composite scores, there is practically no difference between the three methods with the gifted, but a tendency for the part method to be inferior to both the whole and the progressive part with the normal group.

Summary of Results on Poetry Material

1. Under the experimental conditions employed, there are no valid differences between the whole, progressive part and part methods in either group with either V or V + S scores in the learning of 12 lines of poetry, or in the retention after a 24 hour interval.

2. In the percentage of retention, the normal group shows more variation than the gifted between the three methods, mainly in the direction of an advantage of the whole. Such variations which appear, however, can be considered only as indicative of possible tendencies, since all the differences between the three methods in learning and retention are unreliable.

Intelligence and Learning

The comparison of the normal group with the gifted in learning and retention scores, irrespective of learning method, is significant, although of incidental importance with respect to the whole-part problem. In Table 11 the differences between the two groups are presented in terms of the percentage the mean score of the normal is of the mean score of the gifted subjects. All of these differences are reliable, since they are from 3 to 12 times their sigmas. The superiority of the gifted group is apparent throughout the table, being greater with poetry material than with vocabulary, and greater in retention than in learning. The average percentages for the three methods in both of the two experiments with each type of material are as follows: with vocabulary, the normal children learned 46 percent, and retained but 35 percent, of what the gifted learned and retained; the com-

TABLE 11

COMPARISON OF GROUPS IN $\frac{\text{MEAN SCORE OF NORMAL}}{\text{MEAN SCORE OF GIFTED}}$

Learning						Retention					
Whole		Prog. P.		Part		Whole		Prog. P.		Part	
Vocabulary											
1.	3.	1.	3.	1.	3.	1.	3.	1.	3.	1.	3.
48	45	39	33	58	54	43	34	29	39	36	29
Poetry. V Scores											
2.	4.	2.	4.	2.	4.	2.	4.	2.	4.	2.	4.
11	14	9	11	19	14	3	5	.8	3	4	3
Poetry. V + S Scores											
26	31	21	28	34	32	13	16	7	16	10	15

posite poetry score of the normal group was 29 percent of that of the gifted in learning and 13 percent in retention; while in terms of *verbatim* scores, the normal subjects were only 13 percent of the gifted in learning and but 3 percent in retention. In other words, in *verbatim* learning of poetry,

TABLE 12

COEFFICIENTS OF VARIATION

Method	Group	Learning				Retention			
		Vocabulary		Poetry *		Vocabulary		Poetry *	
		1	3	2	4	1	3	2	4
Whole.....	Gifted	31	45	54	55	36	67	77	73
	Normal	54	47	111	68	69	94	154	260
Prog. P.....	Gifted	36	50	66	50	47	89	86	71
	Normal	47	77	112	107	83	100	466	220
Part.....	Gifted	50	61	39	55	62	85	64	79
	Normal	59	84	78	95	95	154	193	171

* V Scores.

where the difference is greatest, the gifted children learned about 8 times, and retained about 33 times, as much as the normal children. Not only did the gifted group learn and retain more, both absolutely and relatively since they show a consistently greater percentage of retention, but their variability, as measured by the coefficient of variation (Table 12), was less than that of the normal group in every comparison of the two groups in the three methods in all four experiments. This difference in variability parallels the difference in size of the scores, being greater with poetry material than with vocabulary, and greater in retention than in learning.

Interpretation of Results

Vocabulary Learning

The results of this study, *i.e.* the reliable superiority of the whole method over the pure part (with both groups and with both types of vocabulary), agree with those of Neumann [18] and Brown,[19] the only other two investigators who used the whole and pure part methods with paired associates under partial learning conditions. As was pointed out in the Introduction, Neumann found the whole method consistently superior to the pure part with five nine- and ten-year old subjects in the learning and retention of lists of seven French-German pairs when each list was given 15 repetitions, or the same amount of time (4′–15″) with each method, and with one nine-year old child in the learning and retention of lists of eight Latin-German pairs when each list was given 10 repetitions. Brown found the whole method reliably superior to the pure part with 511 college students in the learning of lists of 12 English words paired with two-syllable nonsense words when each list was given 12 repetitions with the whole method and 13 with the part. Neumann tested reverse association, while in Brown's, as in this study, forward association was tested.

The probable explanation of this superiority of the whole method over the pure part in the partial learning of lists of

[18] G. Neumann, *op. cit.*

[19] Warner Brown, Whole and part methods in learning, *J. Educ. Psychol.*, 1924, 15, 229–233.

not over 12 pairs is the greater distribution of practice for each pair afforded by the whole method: repetitions of each pair in the whole method are separated by the time taken to recite the rest of the list, while, in the part, they occur in immediate succession. This explanatory principle of distribution of practice for each pair has experimental support in the data of three of Ephrussi's series,[20] in which three subjects consistently show an increased efficiency in the learning of lists of five and six pairs of nonsense syllables with an increase in the distribution of repetitions for each pair. The whole method (which had been found inferior to her distributed part method) was improved by the distribution relatively more than the part, since the differences between the two methods decreased under the conditions of greater distribution. It is unfortunate that Ephrussi did not employ a pure part method so that her experiment could be directly compared with Neumann's and Brown's investigations and with this study. However, her results at least indicate that, under certain experimental conditions, both the absolute and relative efficiency of methods of learning paired associates vary directly with the amount of distribution of practice given each pair.

What has been said in regard to the distribution of practice as an explanatory principle of the superiority of the whole method over the pure part will apply also to the superiority of variations of the part method (Neumann's mixed method and the progressive part in this study) over the pure part, in which the distribution, while not as great as in the whole method, is greater than in the pure part.

Vocabulary Retention

The greater relative advantage in vocabulary retention of the whole over the part method with the normal than with the gifted children is a result, as was pointed out before, of the fact that the normal group shows a greater percentage of retention with the whole method (which had been the more efficient method in learning) than with the part, while the

[20] P. Ephrussi, Experimentelle Beiträge zur Lehre vom Gedächtnis, *Zsch. f. Psychol.*, 1904, 37, 171–177.

percentage of retention with the gifted group is practically the same for all learning methods. However, this difference in percentage of retention in the learning methods with the normal subjects is probably not a true difference, as the following analysis will indicate, but an artifact resulting from the greater number of low scores with the less efficient part method. An analysis of the normal children's scores with the whole and part methods in learning and retention of vocabulary gives the following results: In Experiment 1, with the part method, 25 percent of the children did not learn even one of the 10 Turkish-English pairs, whereas only 9 percent had such a low score with the whole method. (Since not one of these subjects with either method recalled one pair, *i.e.* none showed reminiscence) the greater percentage of retention with the whole method (72%) than with the part (52%), based on the mean score of the group, is in part, at least, due to the fact that 14 percent more of the group with the whole method learned enough to give them a chance to recall any of the material. The same condition is found in Experiment 3, since 39 percent of the children with the part method, compared to 26 percent with the whole, did not learn even one of the 10 nonsense syllable-English pairs.

Poetry Learning and Retention

In considering the reliable differences found between the methods in both groups with vocabulary material compared to the lack of any such reliable differences with the poetry material, the factor of practice with learning methods previous to the experiment must be kept in mind. Apparently the children in both gifted and normal groups had had practically no experience with learning of the paired associate type, since not one, when questioned on the first day of the experiment with vocabulary material, could remember having learned lists at all similar to the test material. Obviously, then, these subjects did not come to the experiment with firmly established habitual learning methods. The condition was quite otherwise with the poetry material. Questioning each subject on the first day poetry material was used gave

the following results: not one of the normal group habitually employed the whole method—62 percent learned 'verse by verse' and 38 percent learned 'line by line'; of the gifted group, 68 percent learned 'verse by verse,' 19 percent learned 'line by line,' while only 13 percent by the whole method. All but one of these subjects who habitually used the whole method did it because they had been previously instructed to do so by some teacher in a lower grade. The practice factor is thus against any superiority of the whole method with poetry learning, while the reason for the lack of superiority of either part methods lies probably in the form of the three learning methods used: the two part methods differed from the whole in only the first two thirds of the time allotted for learning, since the last third was devoted to complete readings of the entire poem.

Summary

A study of the learning and retention after 24 hours of two types of material, lists of 10 paired associates and poems of 12 lines, by two groups, in each of which were 30 nine- and ten-year old school children, a gifted group with a mean I.Q. of 151 and a normal group with a mean I.Q. of 99, with three learning methods, whole, progressive part and pure part, gave the following results:

I. The whole method is reliably superior to the pure part in the learning and retention of both types of vocabulary with both gifted and normal groups. In learning, this advantage of the whole is relatively, as well as absolutely, greater with the gifted group. With poetry material, there are no reliable differences between the two methods in learning or retention with either group.

II. The only reliable difference between the whole and progressive part methods with either type of material is the superiority of the whole with the normal group in the learning of the nonsense syllable-English pairs.

III. The only reliable difference between the progressive part and pure part methods is the superiority of the progressive part with the gifted group in the learning of the nonsense syllable-English vocabulary.

IV. Irrespective of learning methods, the gifted group learned and retained more, both in absolute amount and in percentage of retention, and are less variable than the normal group, with both types of material.

Conclusions

I. The I.Q. is a factor conditioning the relative efficiency of the whole, progressive part and pure part methods in learning. Its efficacy as a factor is apparent, at least, in a comparison of gifted and normal children.

II. Type of learning material is also a factor, which, however, may be a function of the amount of practice and the kind of part methods used.

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THE RELATION OF FREQUENCY AND EXTENT OF ACTION CURRENTS TO INTENSITY OF MUSCULAR CONTRACTION

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Negative variation or action current of muscle was first observed by Mattuecci in 1840 but its discovery is attributed to du Bois Reymond. du Bois Reymond conceived the electrical phenomena of muscle as being caused by a surface of positive and negative electromotive particles. More recent conceptions favor some form of the ' membrane theory ' which explains electrical manifestations of muscular tissue as the result of ionic concentrations at interfaces within the muscle cells.

The earliest observations of electrical response of muscle were made with the astatic needle galvanometer. Later the capillary electrometer, and the string galvanometer were used for recording action currents. All of these instruments possess inertia sufficient to prevent the accurate recording of some of the more rapid action current oscillations. The need of an inertialess system for recording physiological currents has been satisfied by Erlanger and Gasser in the perfection of the Cathode Ray Oscillograph. Its uses however in studies of the present sort are somewhat limited.

Ever since the discovery of electrical phenomena during muscular contraction, experimenters have been interested in the frequency and the extent of the negative variations or action currents. They have used widely varying methods in attempts to secure information about the electrical changes during contraction. Some have used excised muscle-nerve preparations with artificial stimulation, others have used intact muscles with various kinds of stimulation while still others have experimented upon muscular contraction caused voluntarily and reflexly in the human body. There are dis-

advantages in all of these methods. It is felt, however, that the best means of determining a relationship between intensity of muscular contraction and frequency of action current oscillations, is to study the contracting muscle in its normal physiological setting.

One of the earliest investigators of action currents of human muscles was Piper (1). He worked with the string galvanometer upon voluntary contraction of various skeletal muscles. With his electrodes placed upon the skin over a forearm flexor he determined that a fairly regular series of action currents of about 50 per second could be obtained during voluntary contraction. He further determined that regardless of the intensity of the contraction, the frequency of the action currents remained constant but that the amplitude varied. Since by stimulating the motor nerve 50 times per second Piper was able to produce the same response as obtained in voluntary contraction, he infers that the central nervous system innervates the muscle with approximately 50 impulses per second and that the action current rhythm is accordingly the same rhythm as that of the central nervous system. In addition to the dominant frequency of about 50 per second Piper found also a variable number of smaller waves.

Buchanan (2) using a capillary electrometer repeated Piper's work but did not obtain the same results. She found two distinct rhythms, one of waves at the rate of 4 to 14 per second and another composed of small waves which she calls wavelets at the rate of 40 to 100 per second. By changing the temperature of a frog's gastrocnemius she found that she could alter the frequency of the wavelets but not of the waves. By heating the cord and keeping the temperature of the muscle constant she varied the frequency of the waves but not that of the wavelets. She concludes that the wavelets do not correspond with any central nervous system rhythm but indicate a rhythm intrinsic of muscle. She believes that the action current waves found by Piper and herself in human muscles during voluntary contraction are of the same nature as the wavelets of her frog records since the frequencies are so

similar. Piper doubts, however, that the action current rate of 50 action current oscillations per second is of peripheral origin since by stimulating the motor nerve with induction shocks 300 times per second he finds a corresponding action current rhythm in the muscle.

Garten (**3**) in a comparison of nerve and muscle records taken from a rabbit found a close correspondence in the two tissues and concluded that the muscle affords a true record of the discharge of nerve impulses from ganglion cells. Dittler and Garten (**4**) found that action currents from the phrenic nerve during breathing corresponded closely with action currents from the diaphragm. Both frequencies were 70 oscillations per second.

Forbes and Rappleye (**5**) in changing the temperature of the forearm muscles found a decrease in frequency and an increase in amplitude of action current waves when the arm was chilled and a less pronounced increase in frequency with a decrease in amplitude when the arm was heated. They conclude that action currents of muscle are not an index of the rhythm of the central nervous system. They agree with Buchanan that the rhythm of muscle does not follow the rhythm of the motor nerve impulses but depends upon the condition of the muscle itself. Forbes and Rappleye explain the irregularity as being due to certain fibre groups acting out of phase and suggest that where the oscillations are large and rhythmical the majority of the muscle fibres of a group are responding in unison or synchronously. They also think that although the frequency of the nerve impulses may be very high, perhaps 800 per second, they may cause a muscle of an intrinsically low frequency to respond at only 50 per second due to the passage of ineffective motor impulses during the period of the muscle's refractory phase. Forbes and Rappleye agree with Piper that the rhythm of the voluntary muscular response in the absence of fatigue is independent of the strength of contraction.

Dusser de Barenne and Brevee (**6**) disagree with Buchanan, Forbes and others who say that the action current rhythm of muscle is of peripheral origin or a function of the

muscle itself. Dusser de Barenne and Brevee found while working on cats and frogs that by transection at the medulla oblongata and by local narcosis of the sensory spinal mechanism so that centripetal impulses are cut off from motor neurones, they could reduce the frequency of action currents. By continued narcosis they succeeded in reducing the frequency of action currents of muscle to 50 or 70 per second. Upon the basis of this experiment they conclude that the motor neurones supply a 50 to 70 per second intrinsic impulse rhythm but that during contraction various centripetal impulses, as proprioceptive impulses set up in the muscle are superimposed upon the motor impulses to cause the action currents of muscle to become more frequent and irregular. They further believe that the frequency of the action currents under central innervation for various strengths of contraction remains the same but that the amplitude of the action current waves increases with the stronger contractions.

Cooper and Adrian (**7**) alternately cooling the muscle and spinal cord of frogs found the greatest change in action current rhythm of the reflex myogram when the spinal cord was cooled. Hence they conclude that the action current rhythm of muscle follows exactly the frequency of discharge of the spinal cord. The fact that a muscle when stimulated reflexly will not give a regular response at a frequency greater than 120 to 160 per second (in mammal) whereas it will respond regularly at 300 to 400 per second when the motor nerve is stimulated, leads them to believe that the frequency of the electromyogram is determined by the spinal centers and not by the muscle.

Athanasiu (**8**) in his last work published after his death found that in voluntary contraction of the flexor muscles of the fingers and from reflex contraction of a frog's gastrocnemius there were two types of waves. The large irregular waves of a frequency of from 70 to 150 per second he believed were of muscular origin as far as energy is concerned because they represent the action current which accompanies muscle twitches. As to their frequency and amplitude, however, they depend upon the nervous system. The small regular

waves of a frequency of from 300 to 500 per second are of nervous origin and represent the action current which accompanies the ' nervous motive energy.' Since the rhythm of the ' electro-muscular oscillations ' is dependent upon the rhythm of the ' electro-neuromotive oscillations,' Athanasiu says that anything affecting the nervous centers will affect both. Athanasiu believes that there is a definite relationship between the number of ' nervous motive vibrations ' and that of the muscular response in both voluntary and reflex contractions. He feels that there is an average of four nervous vibrations to one muscular response or twitch. Hence if there is a reduction in impulses from nerve centers there is a corresponding reduction in muscular response according to the above ratio.

Gasser and Newcomer (**9**) working with dogs found that simultaneous records taken from the phrenic nerve and the diaphragm show every wave in the muscle to be produced by a corresponding one in the nerve.

Richter (**10**) using a Hindle string galvanometer obtained electromyograms from the same muscles during reflex and voluntary contraction. Action currents during reflex contraction were taken from the forearm muscle of newborn infants during the reflex-grasping response. Action currents during voluntary contraction were obtained from voluntary grasping (using a hand dynamometer) and by voluntary hanging in adult subjects. Richter describes the electromyograms from voluntary contraction of the forearm muscles as being composed of two types of waves, the primary, at a frequency of from 5 to 65 per second and the secondary, at a frequency of from 180 to 250 per second. In addition to these two frequencies he found that at certain intensities of contraction irregular projections appear on the large waves. These he calls ' Nebenzacken.'

Richter's results correspond with those of Wachholder (**11**), in that the frequency of the large waves is dependent upon the intensity of the contraction. With weak intensities of contraction he finds the action current frequency to be very regular and between 5 to 15 per second. With increased

contraction the waves become more frequent but remain irregular until the intensity of the contraction reaches a certain stage. At this point a quite regular rhythm appears. When maximum contraction is attained the waves become irregular again and a frequency as high as 160 oscillations per second is recorded.

He determined further that with increased intensity of contraction the amplitude of the waves increased up to a certain point after which it decreased.

The projections on the large waves or the so-called 'Nebenzacken' are present only when the frequency of the large waves is below 55 per second.

Richter believes that the large primary waves are produced by proprioceptive impulses and the fine secondary waves by impulses from higher centers. The impulses from the higher centers cause tension in the muscles which in turn serves as greater stimulation for proprioceptors thus causing increased contraction and consequently sending out a greater frequency of proprioceptive impulses. He accounts for the projections on the large waves or the 'Nebenzacken' on the basis of a lack of synchronization of the proprioceptive impulses from the end organs in the muscles.

In summing up the general findings of experimenters in regard to the relation of intensity of muscular contraction to the frequency and extent of action currents we note considerable disagreement among them. Piper, Dittler, Forbes, Garten, Dusser de Barenne and others find in various kinds of contraction under central innervation that the frequency of action currents does not vary with the strength of contraction. Most of these experimenters further maintain that the amplitude varies with the intensity of contraction. Contrary to these findings Richter has shown that with increased intensity of contraction the action current frequency increases up to a certain point where the waves become more regular and synchronous. Beyond this synchronous stage, and on up to maximum contraction he finds a still further increase in frequency. The amplitude also increases with intensity of contraction up to a certain stage beyond which it becomes smaller again.

In regard to the nature and origin of the various types of waves we find likewise considerable disagreement. Upon the basis of the work done by Adrian and Zotterman (**12**) and by Richter it seems quite definitely proved that the primary waves have their origin in the reflex arc as the result of proprioceptive impulses while secondary waves have their origin in a higher mechanism concerned with voluntary activity.

Our results, although differing widely from most and in some respects from all previous findings, agree very well with the theories of Richter concerning the origin and nature of the various types of electromyographic waves.

Apparatus

The apparatus used in this study has been described in detail by Travis and Hunter (**14**). Briefly it consists of a three-element Westinghouse Oscillograph, a three stage resistance coupled amplifier and a General Radio low frequency oscillator. The super-sensitive element which was used to record action currents will respond 20,000 times per second. An idea of the relative instantaneity of response of the element may be gained by an examination of Fig. I. In this record the film was moving at about three feet per second. It is to be noted further that the element is completely damped. These facts justify us in assuming an extremely faithful recording of our action current frequencies which were between 300 and 600 oscillations per second.

The over-all deflection range for various frequencies with a constant input voltage is given in Fig. III. Here it is seen that the curve is practically flat between 200 and 1200 oscillations per second. This means that the amplifying-recording unit (amplifier and oscillograph) responds equally well to all frequencies within this range. Inasmuch as our action current frequencies were always within these limits we feel that we can rely absolutely upon the accuracy of the amplitudes recorded. The ability of the amplifier to respond to a pulsating wave is demonstrated in Fig. II.

For the bulk of the work we used two brass electrodes, two inches in length and one quarter inch in width, covered

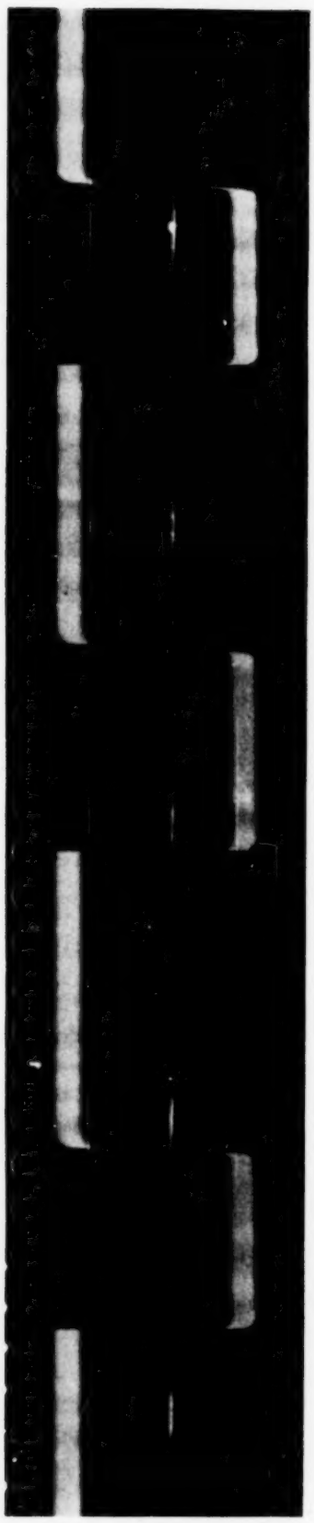


FIG. I. A photograph of a square wave illustrating the relative instantaneity of response and the complete damping of the super-sensitive oscillograph element.

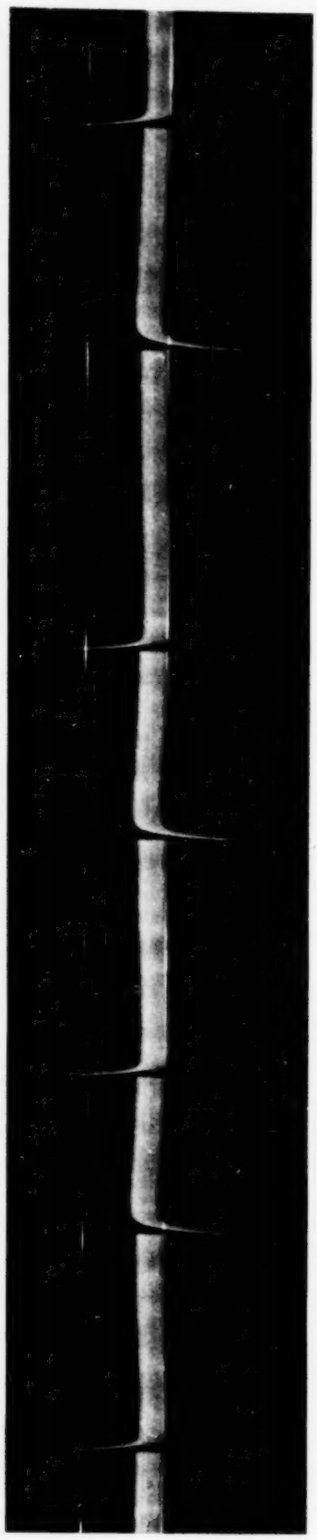


FIG. II. A photograph of a pulsating wave showing the ability of the amplifier to respond to such types of signals.

with canton flannel which was saturated with saline solution. They were fastened approximately one centimeter apart over the motor point of the muscle under consideration. The electrodes were curved slightly to fit the curvature of the leg or arm and were held in place by rubber bands.

The special needle electrodes used in a part of the work consisted of two fine silver wires sharpened to needle points and fused into fine glass tubing. The bare ends of the silver needles extended one inch beyond the glass insulation. The

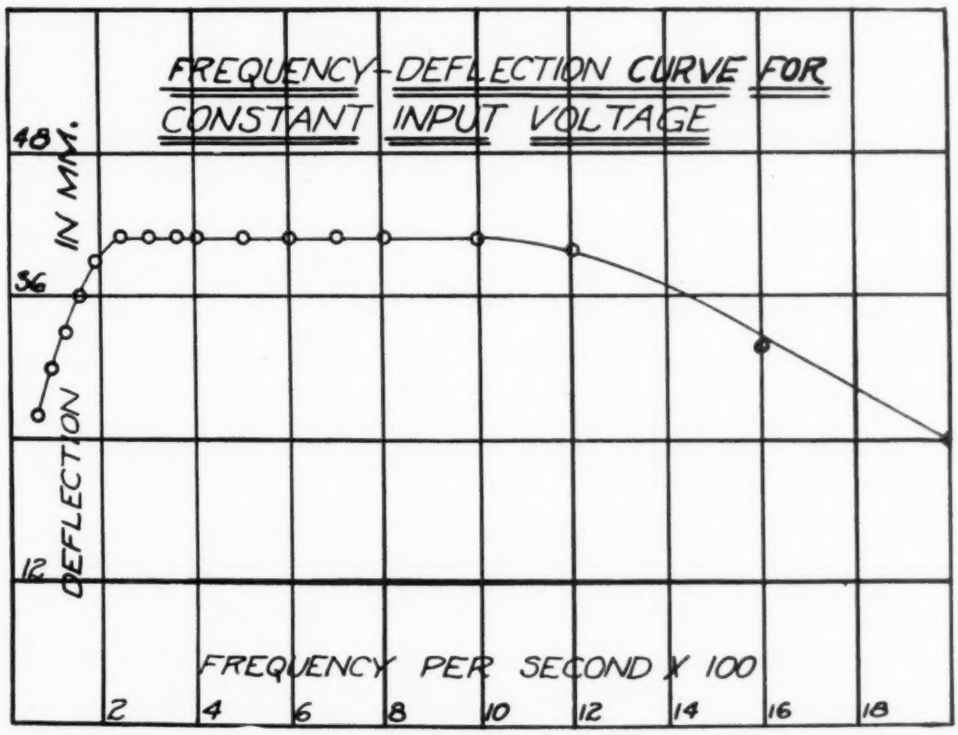


FIG. III. The frequency-deflection curve for a constant input voltage of the amplifying-recording unit (amplifier and oscillograph).

exposed portion of the silver needles was covered with a very thin coat of bakelite varnish which served to insulate them from the skin and other tissues. The ends of the needles were bared two millimeters and coated with silver chloride to prevent polarization. These needles were approximately one centimeter apart. With such a set of electrodes it is possible to study the action of a very small number of muscle fibres and to avoid the effects of electrical resistance of the skin and of the subcutaneous fascia over the muscle itself.

All recording was done on Eastman standard size superspeed motion picture film.

The Smedley hand dynamometer was used to measure various intensities of contraction of the forearm muscle during voluntary flexion of the digits.

Methods of Procedure

Procedure I.—The subject gradually increased the amount of the grip until the pointer on the dynamometer indicated 10 kilograms and then gradually relaxed until the pointer returned to zero again. After a sufficient length of time for any fatigue effects to wear off (usually one to two minutes) the subject gradually increased to 20 kilograms intensity and gradually returned to zero again. This procedure was continued with various degrees of intensity in an ascending series, usually at 10 kilogram intervals, until a maximum contraction was reached.

Although precautions had been taken to prevent fatigue from being a factor it seemed well to reverse the process. Procedure II was then carried out with a few of the same subjects tested in Procedure I.

Procedure II.—Procedure II was identical with Procedure I except that the subject began with his maximum contraction and with proper rest periods interspersed continued in a descending order with various degrees of intensity.

Procedure III.—Procedure III incorporated the descending order of contraction values as described in Procedure II but with the use of constant intensity of contraction rather than a gradual increase to the desired intensity and then a gradual decrease to zero. Here the subject reached immediately a maximum contraction and maintained it for a second or less.

Procedure IV.—For comparing action current frequencies and amplitudes during reflex contraction with those during voluntary contraction the rectus femoris muscle was selected because of the comparative ease in obtaining both types of response from it. The subject was seated comfortably in a chair with his right leg suspended over an insulated iron

standard. The bar of the standard was placed at such a height that a slight amount of tension was produced in the executant muscle. The leg hung so as to move freely when the patellar tendon was struck. The subject was told to relax and close his eyes. After allowing ample time for recovery following several knee jerk responses, records of voluntary contraction were taken with the electrodes in the same position upon the muscle. The subject was told to gradually extend his foot until it had reached a horizontal position and then allow it to slowly return to its original position.

We had no check on the exact amount of contraction in either the reflex or the voluntary extension of the foot. For practically all subjects the foot was raised higher in voluntary than in reflex activity which might mean that contraction was greater in the former than in the latter type of movement. To partially eliminate this possibility we took the average frequency of the action currents in the voluntary record which was based upon readings obtained over the entire range of extension, from minimum to maximum and return.

Procedure V.—Here Procedure III was followed in using three different methods for leading off the action currents from the muscle. The first method employed the plain brass electrodes placed on the skin over the muscle, the second method the needle electrodes inserted in the muscle mass, and the third the plain brass electrodes placed over the holes in the skin made by the needles. The needle electrodes were one centimeter apart and were so placed in the arm muscle that they entered an area previously covered by the plain brass electrodes. The needles were inserted without the use of an anæsthetic.

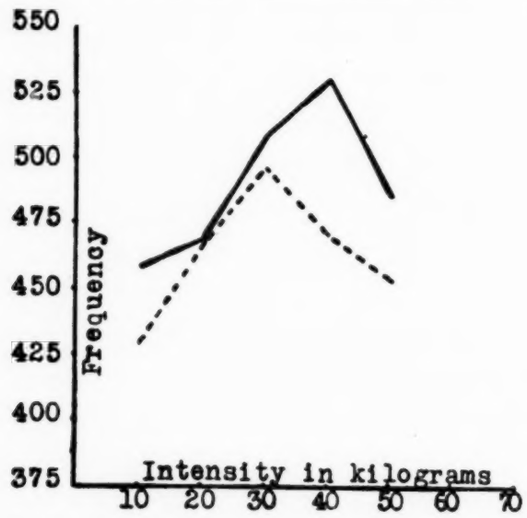
Method of Reading Film.—In determining the frequency of the action current waves every visible wave was counted regardless of its size. The amplitude of every diphasic wave was read in millimeters. It was taken as the distance of the excursion without reference to any particular base line.

Results

The results in this study were obtained from twenty-five normal adult individuals. Three of them were women. Several of the subjects have served more than once, some as often as four times.

Relation of Intensity of Contraction to Frequency of Action Currents

In general all subjects regardless of the method of procedure gave, up to a certain amount of contraction, an increase in the action current frequency with an increase in the intensity of contraction. Beyond a certain amount of contraction, usually 30 or 40 kilograms, the frequency of the



F.G. IV. A graph of the action current frequency readings for various intensities of voluntary contraction. The broken line = the left forearm and the solid line the right forearm.

action currents decreased. This is shown in Fig. IV. On the average the action current frequency decreased at 70.5 percent of the maximum contraction for the right forearm and at 59.6 percent of the maximum contraction for the left forearm in right-handed subjects. In the case of three left-handed individuals we found that the action current frequency decreased relatively earlier in the right than in the left forearm. These findings suggest a possible means of determining the native physiologic lead.

Relation of Intensity of Contraction to Amplitude of Action Currents

In general all subjects regardless of the method of procedure gave an increase in the amplitude of action currents with an increase in the intensity of contraction. The amplitude unlike the frequency of the action currents did not decrease beyond a certain amount of contraction (Fig. V).

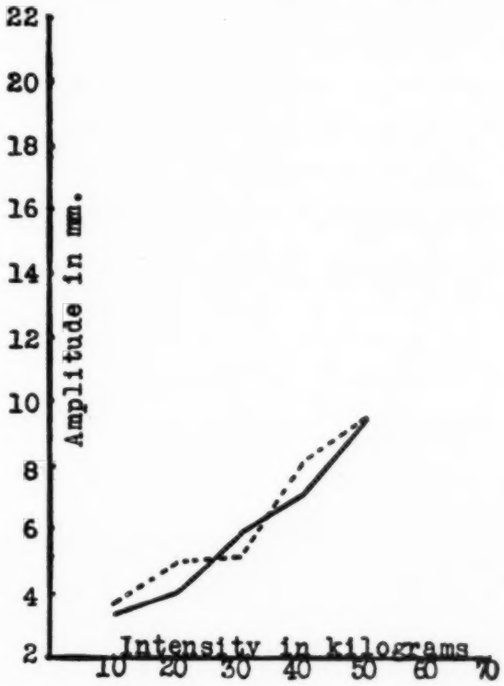


FIG. V. A graph of the action current amplitude readings for various intensities of voluntary contraction. The broken line = the left forearm and the solid line the right forearm.

A Comparison of Action Current Frequency in Voluntary and in Reflex Activity

In an effort to bear out some of the conclusions reached by Richter (10) concerning the differences between action currents from reflex and voluntary contraction an attempt was made to compare action current frequencies in the same muscle during both types of activity (Procedure IV). No attempt was made to control the intensity of the contraction in either case so the records are not strictly comparable in respect to intensity. We found that action currents from reflex contraction present consistently a greater frequency

than those from voluntary contraction of the same muscle. The mean frequency for voluntary action currents was 401 and for reflex action currents 437. In view of the fact that the arc described by the foot in voluntary contraction was in every case larger than that of the foot in reflex contraction, our findings seem all the more significant. The voluntary contraction being of greater intensity than the reflex contraction should have shown the greater action current frequency. Since the reverse was true we feel justified in maintaining that action current frequency during reflex contraction is greater than during voluntary contraction. This is seemingly in disagreement with Richter's findings since he maintains that secondary waves are absent in his reflex records which of necessity reduces the frequency much below the frequency rate of his voluntary records.

Periodic Fluctuations in Extent of Action Currents

In some of the voluntary records a definite periodic fluctuation in the amplitude of the action current waves has

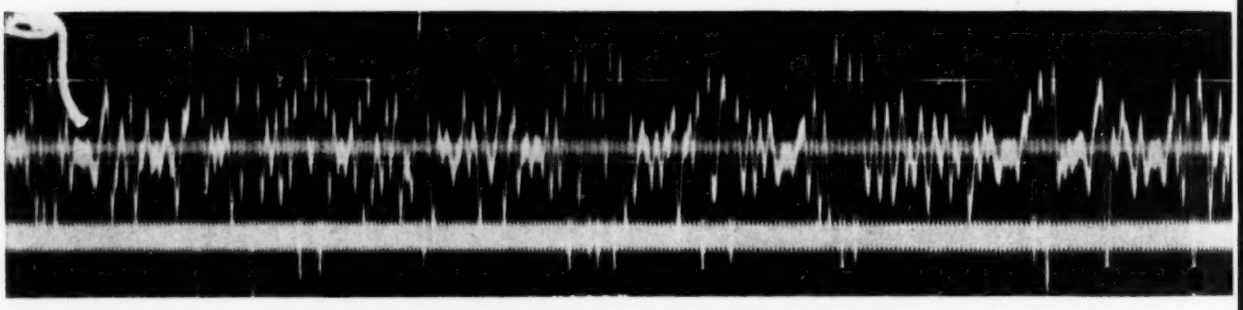


FIG. VI. A typical record of action currents in voluntary contraction of the flexors of the digits. Time is recorded in thousandths of a second.

been noticed (Fig. VI). This same phenomenon has been reported by Travis and Hunter (**15**). They found that their action current records resembled "a modulated wave, that is, a wave having the amplitude of its oscillations varied periodically." They maintain that this "modulated wave is made up of an audible or principle frequency and an inaudible frequency." "The inaudible frequency (10 to 12 per second) is composed of periodic variations in intensity of the audible

frequency (300 to 600 per second) and is termed the 'envelope.'"

The presence of these so-called 'envelopes' indicated that perhaps a periodicity in frequency might also exist. The action current records showing periodicities in amplitude were re-read for frequency in finer units (50ths of a second) than we had been accustomed to reading them. The readings were then plotted in an attempt to discover any periodici-

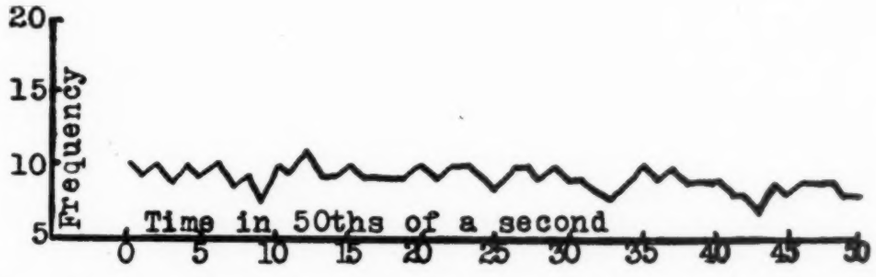


FIG. VII. A graph of action current frequency readings from a film which showed periodic fluctuations in the extent of the action currents.

ties in frequency which might be present. Figure VII represents the plotted frequencies of a typical record. It seems from these graphs that there are no periodic fluctuations in frequency corresponding to the periodic fluctuations in amplitude.

The Effect of Fatigue Upon the Frequency and the Amplitude of Action Currents

In our attempts to control fatigue as a factor in our experiments it was thought advisable to determine just what effect fatigue might have upon the frequency and the amplitude of action currents during favorable conditions for it, such as, constantly maintained contraction. Table I shows very clearly that both the frequency and the amplitude of action currents decrease during prolonged contraction of the muscle. That fatigue could not have played a part in our findings with Procedures I, II, III and V is indicated in several ways. First, the contractions were maintained never longer than 3 seconds which is insufficient time for fatigue to cause noticeable changes in frequency or amplitude. Second, rest periods between various intensities were sufficiently

TABLE I

FREQUENCY AND AMPLITUDE OF ACTION CURRENT WAVES TAKEN DURING A CONSTANTLY MAINTAINED CONTRACTION AT 35 KILOGRAMS OF INTENSITY

Records were taken at 5-second intervals during the contraction.

Time Intervals in Seconds	0	5	10	15	20	25	30	35	40	45	50	55	60	% of Decrease
Subject T														
Frequency....	484	482	470	465	447	450	450	452	450	445	425			12.2%
Amplitude...	4.1	4.0	3.8	3.9	3.5	3.5	3.7	3.1	3.0	2.8	2.5			39.0%
Subject E														
Frequency....	479	473	469	456	448	441	438	423	407	404	400	400	397	17.1%
Amplitude...	6.9	6.9	6.4	6.1	6.3	5.7	5.7	5.2	4.9	4.7	4.6	4.1	3.9	43.5%
Subject S														
Frequency....	421	420	418	413	398	385	385	372	373	363	353	352	342	18.7%
Amplitude...	7.3	7.2	7.0	6.7	5.9	5.6	5.4	5.4	5.1	4.9	4.7	4.4	4.1	43.8%
Subject R														
Frequency....	430	425	415	410	410	400	396	375	364	360	355	346	338	21.4%
Amplitude...	6.6	6.4	6.3	6.0	5.9	5.5	5.4	5.3	5.0	4.8	4.6	4.3	4.4	33.3%
Subject U														
Frequency....	460	450	428	408	400	393	378	367	355	350	350	350	341	25.8%
Amplitude...	8.1	8.0	7.6	7.4	7.1	7.1	6.9	6.5	6.3	6.3	5.9	5.7	5.4	32.9%

long to allow the muscle to completely recover from any fatigue effects which might have developed. Third, since in the fatigue study the amplitude decreases at a greater rate than the frequency one would expect that if the characteristic drop in frequency was due to fatigue that the amplitude would also decrease. This was not the case, however, and eliminates entirely, it seems, the possibility of fatigue effect influencing our results.

Results Obtained with Different Electrodes

It will be recalled that in Procedure V we used three different methods for leading off the action currents from the muscle. We attempted to control all possible conditions so that the records from all three methods might be directly comparable.

The results indicate that the same general relationships found with our other methods are present in the records obtained by these three methods. There are, however, certain variations in the records by these three methods. The action current frequency with the plain brass electrodes and with the plain brass electrodes over the holes in the skin was

consistently higher than with the needle electrodes (Fig. VIII). This may be due to the fact that the needle electrodes cover a smaller area and consequently pick up action currents from a smaller number of muscle fibres than the brass strip electrodes.

The needle electrodes and the electrodes over the holes

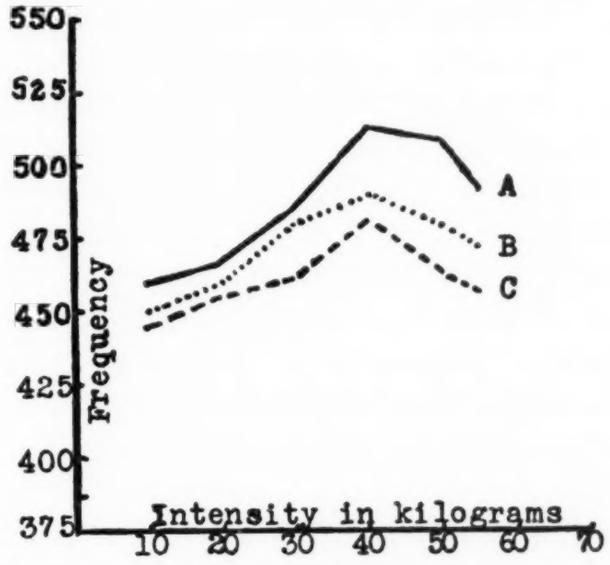


FIG. VIII. A graph of action current frequency readings from records obtained with three different methods of leading off the action currents from the muscle. *A* = plain brass electrodes on the skin, *B* = plain brass electrodes over needle holes in the skin, and *C* = needle electrodes in the muscle.

in the skin gave a greater amplitude of action currents than the plain brass electrodes over the muscle. This indicates very clearly that with the needle electrodes and the plain brass electrodes over the holes in the skin the effect of skin resistance was reduced. Richter (10) has maintained that skin resistance is entirely eliminated by merely piercing the skin and placing ordinary electrodes over the holes. Our results show that the entire effect of skin resistance is not eliminated when the plain brass electrodes are placed over holes in the skin, for the insulated needle electrodes which are absolutely isolated from the skin show even lower frequencies and greater amplitudes than the plain electrodes over the needle holes.

Discussion of Results

Our findings agree with those of Richter (**10**) in that there are three types of waves present in records of voluntary action currents. We wish to add, however, that these three types of waves are not always distinguishable. For this reason we are reluctant to base conclusions in regard to frequency and amplitude on the basis of classified types.

Richter attributes the large primary waves of his action current records to proprioceptive impulses reflexly acting upon the muscle. The work of Liddell and Sherrington (**13**) on ' myotatic reflexes ' as well as that of Adrian and Zotterman (**12**) and of Dusser de Barenne (**6**) are supporting evidence for Richter's conclusion that action currents are dependent in part on proprioceptive impulses.

In regard to the ' Nebenzacken ' (small projections on the sides or in the troughs of waves) Richter concludes, especially on the basis of the work by Adrian and Zotterman (**12**), that these waves are due to irregularity of proprioceptive impulses which are out of phase. In his work he finds that as contraction approaches a certain intensity the proprioceptive impulses evidently become synchronized somewhere in the reflex arc with the result that the action current waves become more regular and the ' Nebenzacken ' or projections on the waves disappear.

The secondary waves he finds are of lower amplitude but occur at a greater frequency. He concludes that these waves are dependent upon voluntary impulses from higher centers, chiefly because of their absence in contractions of reflex nature.

This view concerning the origin and nature of action current waves is supported by our results. We find that as intensity of contraction increases the action current frequency likewise increases up to a certain point (usually 30 or 40 kilograms) after which the frequency not only ceases to increase but decreases with further intensity of contraction. The initial increase in frequency with the increase in intensity may be accounted for by the fact that as the intensity of contraction increases more end-organs are brought into action

and the frequency of impulses from each individual end-organ also increases, consequently causing the frequency of the resulting action currents to become greater. However, these impulses are irregular and out of phase which causes projections on the sides of the action current waves rather than regular waves. When the intensity of contraction reaches a certain point the proprioceptive impulses become synchronized in the reflex arc and cause more regular action current waves in which there is an absence of '*Nebenzacken*' or projections. This regularity is readily observed in our records and since the '*Nebenzacken*' are absent, it naturally results in a reduced frequency. This then accounts for the drop in frequency we find at about 30 or 40 kilograms of intensity of contraction.

Likewise, when the '*Nebenzacken*,' which are usually waves of much lower amplitude than either the primary or secondary waves, are absent, the average amplitude will be greater than when they are present. Furthermore we must recognize the fact that the more muscle fibres brought into operation the greater will be the electrical potential and hence the increased amplitude of action current waves for increased muscular contraction. Also, the increased contraction in each individual fibre may cause a correspondingly greater potential between any two points on its surface.

Two views to account for the factor of synchronization have been offered. Dusser de Barenne and Brevee (**6**) demonstrated an inherent rhythm in the anterior horn cells of the spinal cord which they think may influence impulses. According to them the frequency at which the action currents of any muscle come into phase depends on the inherent rhythm of the motor cells present in the part of the cord with which the muscle is connected. Something also of this nature might be inferred from the work of Cooper and Adrian (**7**), who showed that within certain limits stimulation to an afferent nerve passes through the cord to the muscle essentially unchanged as far as frequency is concerned.

The view that Richter takes and the one which appears to have the balance of evidence in its favor, explains syn-

chronization as being dependent upon the relationships between the time required for each impulse to travel through the reflex arc, the time necessary for the impulse to set up a new proprioceptive response, and the frequency of the proprioceptive impulses. According to this view the length of the reflex arc would determine the frequency at which the action currents would synchronize. The variation we have found in the synchronizing point in different individuals would seem to bear out this conclusion.

There is another possible explanation of our results. It is based upon the fact that impulses to a muscle which reach it during its refractory phase are ineffective. If the intrinsic refractory phase of a muscle is such that only impulses up to a certain limit are effective and any frequency above this limit is ineffective then it follows that at that point the frequency of action currents will not increase further. This is somewhat substantiated by Forbes and Rappleye, who showed that nerve impulses of a very high frequency caused by artificial stimulation of the motor nerve will not cause the muscle to respond at the same frequency, but only at some lower frequency intrinsic of the muscle.

The final explanation of the frequency and amplitude of action current waves during various degrees of contraction will probably depend upon further experimentation with single isolated nerve fibres and individual end-organs, such as the work of Adrian (**16**), Adrian and Zotterman (**12**), Adrian and Bronk (**17**), Pratt (**18**) and others.

Our results in regard to reflex and voluntary contraction oppose the belief of Richter, who thought that since secondary waves due to voluntary activity are absent in reflex contraction the resulting action current frequency will be lower than in voluntary contraction. We find a consistently higher frequency of action current waves in reflex than in voluntary contraction of the same muscle. It seems to us that this difference in the frequency of the action currents will have to be referred to the central nervous system inasmuch as the same muscle was operating under the same experimental conditions in the two forms of activity. There

are two neurophysiological facts which if properly related might offer an explanation of this finding. The first is that in the functional integration of the central nervous system the most easily demonstrable relationship between higher and lower levels is one of dominance of the former. The greater and lesser irradiation of the higher centers retards and facilitates respectively the activity of their subjacent levels. The second fact is that the rhythmical functioning of the higher levels is slower than that of the lower. Relating these two facts we would expect to find slower rhythms in those activities in which the higher levels are relatively more active and faster rhythms in those activities in which the higher levels are relatively less active. The former type of activity would be represented by the voluntary extension of the foot and the latter by the reflex extension of the foot.

Summary of Results

I. Up to a certain intensity of voluntary contraction there is an increase in the action current frequency with an increase in the intensity of contraction. Beyond a certain amount of contraction, usually 30 or 40 kilograms, the frequency of the action currents decreases.

II. There is an increase in the amplitude of action currents with an increase in the intensity of contraction. The amplitude unlike the frequency of the action currents does not decrease after a certain intensity of contraction has been reached but increases with every increase in contraction.

III. Both the frequency and the amplitude of action currents progressively decrease during sustained muscular contraction.

IV. With a limited number of individuals the frequency of the action currents in voluntary contraction is consistently less than that in reflex contraction of the same muscle.

V. Although periodic fluctuations in the amplitude of the action current waves are often present in our records, no corresponding periodicities in frequency could be determined definitely.

VI. Three different methods for leading off the action

currents from the muscle (plain brass electrodes over the muscle, silver needle electrodes in the muscle, and the plain brass electrodes over the needle holes in the skin) gave the same general relationships between frequency and extent of action currents and the intensity of muscular contraction. However, the needle electrodes gave the greatest amplitude and the least frequency of action currents at any given intensity of contraction. The greater amplitude was undoubtedly due to the elimination of skin resistance and the lesser frequency to a reduction in the number of muscle fibres covered.

VII. In general the action current frequency decreased at a greater percentage of the maximum contraction for the right forearm than for the left forearm in right-handed individuals. The converse was found to be true of left-handed subjects.

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DIFFERENTIATION OF THE HYPNOTIC TRANCE FROM NORMAL SLEEP[1]

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The apparent resemblance between normal sleep and hypnosis was observed very early in the study of animal magnetism. In fact, the very name hypnosis was given to the condition by Braid because of this resemblance. Braid (**4,** 13) called the hypnotic condition a nervous or artificial sleep. But Braid was not misled by the apparent resemblance and stated quite positively (**4,** 49) that hypnotic sleep was not the same as normal sleep. Among those who have agreed with Braid in this respect may be mentioned Wundt, Krafft-Ebing, and Jacoby (**7,** 164). There have been others, however, who have been equally as positive that the hypnotic trance and normal sleep were one and the same thing. Among the early proponents of this view was Bernheim (**2,** 15) who said that ". . . suggested sleep differs in no respect from ordinary sleep." In this, as in many other theoretical points regarding hypnosis, the Nancy school agreed with Bernheim, even classifying the various stages of hypnosis according to the supposed depth of the subject's sleep. While Bechterev (**1,** 23) did not go quite as far as the Nancy school he agrees as to the essential identity between normal sleep and hypnosis, holding that the hypnotic trance is '. . . a special modification of normal sleep.' Pavlov also believes that he has found an intimate relationship between sleep and hypnosis. In his theory, the connecting link between the two processes is inhibition, which he believes may manifest itself as either sleep or hypnosis. The observations which led to this theory were made while working with conditioned reflexes in dogs. If an animal was stimulated with an unrein-

[1] The writer takes much pleasure in expressing his gratitude to Prof. Clark L. Hull for his advice and invaluable assistance and criticism.

forced conditioned stimulus for a period of time the conditioned response was extinguished. Experiments show that such extinction results in the development of inhibitory tendencies. Moreover, it has been shown (**11**, 604) that such inhibitions may spread or irradiate to reflexes involving other parts of the animal's body. The results of this sort of experimental work on inhibition led Pavlov to the conclusion (**11**, 607) that "Sleep is inhibition irradiated over the whole area of the active points of the hemispheres and even over some of the brain below the cerebral hemispheres" and that "Hypnosis is inhibition spread over the usually active parts of the special areas of the hemispheres." According to Pavlov, then, the relationship between hypnosis and sleep is merely a matter of the degree of spread of inhibition.

Such theoretical disagreement as to the relationship between hypnosis and sleep is due to the fact that there is no comparative objective evidence indicating the existence or non-existence of any significant identity between normal sleep and hypnosis. Such a study should first seek for one or more behavioral or physiological phenomena which show dependable objective differentiations between ordinary sleep and the normal waking state (**5**, 200). Phenomena showing such differentiation can then be investigated in hypnosis to see if there is any differentiation between the trance and normal sleep.

One such objective phenomenon is available in the ordinary patellar reflex. It has long been known that the patellar reflex is greatly diminished and, in some cases, entirely abolished during sleep. This diminution of the patellar reflex in sleep was first noted by Lombard (**9**, 58) in 1887. He reported the phenomenon as an incidental observation in his findings on the normal variations of the knee jerk. This note was mainly based on the fact that he obtained on himself a number of extremely low reflex kicks one morning while feeling very drowsy and sleepy. Bowditch and Warren (**3**, 59) confirmed Lombard's results using more subjects and taking more extensive records. They also reported the significant observation that the continuous hammer blows tended

to cause the subjects to sleep more readily, instead of preventing their going to sleep as might naïvely be expected (**3,** 58). Noyes (**10,** 345) working on a case of terminal dementia found that his patient had his patellar reflex entirely abolished during sleep. More recently, Lee and Kleitman (**8,** 149) and Tuttle (**13,** 345) have confirmed very fully the results initially obtained by Lombard and by Bowditch and Warren. Tuttle also reported (as had Bowditch and Warren) that the patellar stimulation caused the subject to fall asleep more easily.

Apparatus

The subject was placed in the modified barber chair (*E*) as shown in Fig. I. This chair had been adapted by replacing the headrest with a padded back and head support. The

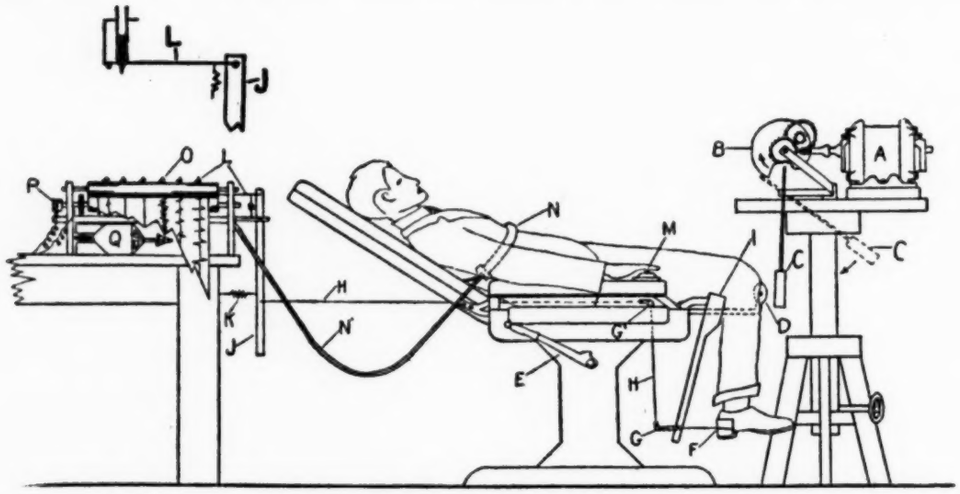

Fig. I. Diagrammatic line drawing of the apparatus showing the position of the subject and the relation of various parts of the apparatus.

footrest was removed and replaced by a backboard (*I*) so arranged that the subject's legs could hang vertically when he was in a reclining position. The backboard also prevented excessive oscillation of the leg following a reflex kick.

The brass stimulus hammer (*C*, *C'*) was of a combination pendulum-lever type. It was 50 centimeters from the fulcrum to the weighed end and weighed 300 grams when supported horizontally by the fulcrum at one point and a spring scale at the end of the bob. The hammer was lifted as a lever by the cam (*B*). When the cut-out portion of the cam

reached the short end of the hammer lever, the latter was released and swung as a free pendulum through an angle of 75° to deliver the stimulus blow. After the stimulation the hammer was caught on the rebound by the cam and again gradually lifted in preparation for the next blow. The power for driving the cam was supplied by a unit consisting of a ¼ h.p. split-phase constant-speed electric motor (*A*) which made 1750 revolutions per minute. This speed was reduced by a worm and gear supplemented by a pair of spur gears to give a final speed to the cam of one revolution in 9.68 seconds. The power unit was covered with a felt-lined box (not shown in the drawing) which shielded it from the view of the subject and reduced the noise to a soothing drone. The whole was mounted on a solid wooden base, braced, and attached to the top of a heavy wooden laboratory stool provided with a convenient height adjustment.

The hammer in falling did not strike the tendon directly. It hit a bamboo rod which was attached at one end to a universal clamp (*D*) bolted to the baseboard (*I*). This clamp permitted the adjustment of the rod so that it passed horizontally in front of the patellar tendon of the left leg. When the hammer struck the rod the blow was transmitted to the tendon. The rod was wound with copper wire so that when it was struck by the hammer an electric circuit was completed which operated an electromagnetic marker automatically giving a graphic record of the stimulation.

In order to secure a graphic record of the leg movements following a stimulation a semicircular strip of tin (*F*) was fastened to the heel of the subject's shoe by means of a heavy rubber band. To this tin strip was attached one end of a fairly heavy fish line (*H*) which passed through several smooth glass elbow joints (*G*, *G'*) to the lower end of the reducing recording lever (*J*). The glass elbows served both as pulleys and guides for the line. They are well suited for such use because of the slight amount of friction in smooth glass tubing. To the short end of the recording lever was attached the pen support (*L*) which was pivoted at the point of attachment to the lever. In the pen support was placed

a glass pen made by drawing one end of a small piece of glass tubing to a fine point. The detailed arrangement of the pen support and pen is shown in the small drawing in the upper left-hand corner of Fig. I. Such a device is well adapted to give a tracing of the leg movements on a horizontal surface. Each millimeter on the record of the knee jerk thus obtained was equivalent to 4.1 millimeters of actual movement of the foot.

The section of record reproduced in Fig. II shows in the

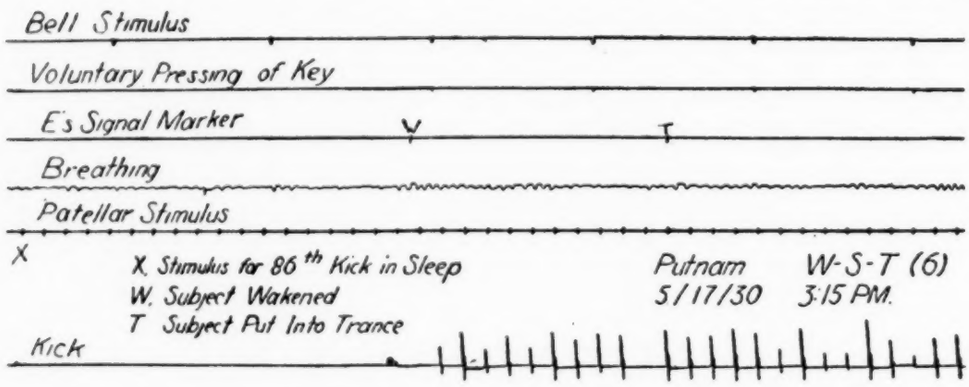

FIG. II. Reproduction of a portion of a typical record.

lowest line a typical tracing obtained with this device while the subject was in each of the three states. At the beginning of the reproduction the subject is asleep and there is an almost complete lack of kick response. The subject was awakened at *W* after which there is an almost immediate recovery of the patellar reflex. About two minutes after waking the subject was put into the hypnotic trance at the point marked *T*. If the "suggested sleep differs in no respect from ordinary sleep," we should expect the knee jerk to disappear at once. It is entirely typical that no observable change whatever takes place.

The record shown in Fig. II was obtained on a specially constructed recording polygraph shown at the extreme left of Fig. I. The polygraph was activated by an adjustable-speed electric phonograph motor. This motor was geared to the lower of a pair of rubber typewriter platens between which was fed twelve-inch adding machine paper from a large roll. Just before passing between the platens the paper was

drawn over a smooth piece of wood two inches wide. Above this were fixed the supports for the glass recording pens, including the one for the knee jerk already described. Four of the pens were connected to electromagnets, one (*O*) was activated by the tambour from the pneumograph, and a sixth pen (*L*) was attached to the recording lever for the kick. The pens and pen supports were all similar to the one illustrated in the small drawing in the upper left-hand corner of Fig. I.

On an extension of the shaft supporting the lower platen was attached a small wooden wheel (*P*) with a contact point partly embedded in its circumference. At each revolution this point made contact with a piece of spring brass pressing against the wheel. This contact closed an electric circuit which gently rang a signal bell. At the same time an electromagnetic marker placed in the circuit gave a graphic record of the ringing of the bell. The bell stimuli appear as notches in the upper line in Fig. II. Since the platen took about 90 seconds to make one complete revolution the bell signals were separated by that interval. While in the normal waking state at the beginning of the experiment the subject was instructed to respond to the bell signal by immediately pressing the push button (*M*), which was conveniently attached to the arm of his chair. These instructions were never repeated for either the trance or sleeping states. The push button operated by the subject was connected to another electromagnetic marker which gave a graphic record of the subject's voluntary response. These responses appear as the notches in the second line from the top in Fig. II. This shows the voluntary response as absent in sleep, quite as one should expect. It spontaneously appears when the subject is awakened and continues undisturbed during the trance, exactly paralleling the results obtained with the patellar reflex. This technique was devised by Reed and Kleitman (**12**, 601) with a view to securing an objective index of the onset of sleep. They report that the response to an auditory stimulus ceases during sleep, without, however, giving any quantitative data.

The pneumograph (*N*) was used to obtain a record of the

breathing in the three states. This appears as the fourth line from the top in Fig. II. In this record the tracing is atypical in that it is shallower than was usually the case. The breathing records have been reserved for more elaborate treatment, but some preliminary measurements tend to support Reed and Kleitman's conclusions that there is little, if any, differentiation between the breathing in the sleeping and waking states.

Method

The general method used to differentiate normal sleep from the hypnotic trance was to determine the relative amplitudes of the knee jerks in these two states. Coincident with this were obtained records of the voluntary response to a gentle auditory stimulus. As mentioned above, this voluntary response had been found to be a good sleep index. A control was also run on each subject and at each session to determine both the relative amplitude of the knee jerk and the percentage of correct voluntary response in the waking state. The patellar reflex and the voluntary response to an auditory stimulus were chosen as indices since they consistently show a marked differentiation between normal sleep and waking. A number of other physiological reactions which were considered for the purpose had to be abandoned because previous investigators had found that they were ineffective in differentiating the waking state from normal sleep.

The plan of procedure was to obtain a series of records containing 100 consecutive kicks in each of the three states (waking, trance, and normal sleep) during a single experimental period. The records were to be practically continuous for all the states on any experimental day. A short waking interval had to be inserted between sleep and trance and between trance and sleep to insure the subject's coming back to a normal condition before passing into the second state. In order to eliminate practice and adaptation effects the records were taken in the following six possible combinations in temporal sequence of waking (*W*), sleep (*S*), and trance (*T*):

W S T	T S W	S W T
W T S	T W S	S T W

Each subject had the initial experimental session on a different combination and had a different combination on each experimental period. The combinations were also presented to the different subjects in different sequences.

Procedure

The pneumograph was fastened about the subject's chest and he was placed in a reclining position in the chair. The tin strip (*F*) was attached to the heel of the left shoe and the bamboo rod adjusted over the tendon by means of the clamp (*D*). The hammer mechanism was then started to see if the patellar tendon was actually being stimulated. If all the adjustments proved correct the motor of the polygraph was then started and the first part of the record, 100 patellar stimulations, was taken. In the experiment from which the record reproduced in Fig. II was obtained the first section of the record was waking. This consumed about fifteen minutes. The subject was then asked to try to go into a normal sleep. During this period, as the reactions of the subject began to indicate sleep, the experimenter frequently spoke to him in a low tone of voice. He asked the subject simple questions and attempted to induce catalepsy but obtained no response. The subjects later uniformly reported not having heard anything. At the end of the period of 100 patellar stimulations, about fifteen minutes, the subject was awakened and remained awake for about two minutes. He was then put into the hypnotic trance for 100 patellar stimulations which again consumed about fifteen minutes. During this period the subject was tested for catalepsy in the same low tone of voice used in the sleeping tests with uniformly positive results.

Subjects

Seven male university students were used in this experiment. They were of varied ages and scholastic training, ranging from freshmen to graduate and professional students. They were all obtained through the University Bureau of Appointments and received a modest compensation for their services. Five of the subjects served on six experimental

days each, one (Sc) on five days, and one (Co) on eight days, giving a total of 43 experimental periods. All except two of the subjects showed complete post-hypnotic amnesia and these two (Ma and Sc) showed a partial amnesia. All of the subjects showed catalepsy readily and this was used as a test of whether they were in a trance at least once during each trance record. After the normal sleep portions of the experiment three of the subjects (Co, Ri, and St) uniformly reported being in a deep normal sleep. The other four subjects usually reported being in a drowsy condition or in a light sleep, although even they sometimes reported having been in a deep or sound sleep. Even when the subjects reported being only drowsy they frequently showed complete or partial amnesia for events happening during the period.

Results

Table 1 gives for the several subjects the mean amplitude of the patellar kick tracings for each successive group of five stimulations during the six or so waking periods served by each subject. Table 2 shows the same for the hypnotic trance and Table 3 for the natural sleeping states. The composite results from all three tables are shown in Fig. III. Here the base line indicates time as measured by the interval required for five stimulations, and vertical distances indicate the mean amplitude of kick tracings of all the subjects during these intervals. An examination of this graph shows that the courses of the kicks in the waking and trance states are practically identical. The fall in both curves is very much alike and there is a fairly constant high level maintained throughout both. Although the amplitude of the kicks in sleep starts in the region of the normal kicks it drops very rapidly. The amplitude of the second fifty kicks is consistently only about a third as great as that of either the waking or the trance states.

The first section of Table 4 summarizes the experimental results for the patellar reflex which have been given in detail in Tables 1, 2, and 3. As pointed out above, there were usually six records for each subject. Each record consisted

TABLE 1

THE MEAN AMPLITUDES OF THE NORMAL WAKING KNEE-JERK TRACINGS OF THE SEVEN SUBJECTS AT VARIOUS STAGES OF THE HUNDRED STIMULATIONS RECEIVED AT EACH EXPERIMENTAL PERIOD

Subject	Mean Amplitudes of Kick Tracings in Millimeters for Successive Groups of Five Stimulations																			
	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to 30	31 to 35	36 to 40	41 to 45	46 to 50	51 to 55	56 to 60	61 to 65	66 to 70	71 to 75	76 to 80	81 to 85	86 to 90	91 to 95	96 to 100
Co	21.4	18.7	15.1	15.7	14.7	17.7	18.0	18.4	15.4	17.8	15.5	13.8	12.4	13.3	16.4	16.0	16.3	16.6	17.1	16.7
Ho	6.1	6.0	5.6	6.4	4.4	4.2	4.5	3.8	4.7	3.5	3.1	4.4	5.7	4.3	3.7	4.3	4.1	4.9	8.1	5.8
Ma	28.2	23.2	21.6	22.5	21.9	22.8	20.9	22.2	19.8	24.8	22.6	22.9	21.1	22.3	20.1	21.5	19.2	21.5	20.1	17.0
Pu	13.8	9.1	10.3	9.6	8.9	8.1	7.2	7.4	7.2	7.9	8.3	6.7	7.1	7.9	6.5	6.6	5.5	5.5	6.8	7.2
Re	18.9	17.0	12.6	15.0	13.4	19.1	13.0	12.9	11.9	10.5	10.9	11.5	11.2	11.3	6.8	8.7	9.1	9.0	10.4	10.7
Sc	9.5	12.4	11.7	12.3	9.5	9.6	11.0	12.4	15.6	12.1	10.8	15.3	11.3	11.1	12.0	13.1	8.4	8.5	10.9	9.6
St	15.9	14.8	11.6	12.7	14.1	17.2	13.9	13.7	12.8	11.6	17.0	11.8	9.2	12.1	8.9	13.7	10.3	9.3	9.3	11.7
Means	16.3	14.5	12.6	13.5	12.4	14.1	12.6	13.0	12.5	12.6	12.6	12.3	11.1	11.8	10.6	12.0	10.4	10.8	11.8	11.2

TABLE 2

THE MEAN AMPLITUDES OF THE HYPNOTIC TRANCE KNEE-JERK TRACINGS OF THE SEVEN SUBJECTS AT VARIOUS STAGES OF THE HUNDRED STIMULATIONS RECEIVED AT EACH EXPERIMENTAL PERIOD

Subject	Mean Amplitudes of Kick Tracings in Millimeters for Successive Groups of Five Stimulations																			
	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to 30	31 to 35	36 to 40	41 to 45	46 to 50	51 to 55	56 to 60	61 to 65	66 to 70	71 to 75	76 to 80	81 to 85	86 to 90	91 to 95	96 to 100
Co	18.8	17.9	13.6	13.0	13.7	14.6	14.4	13.9	13.5	14.1	14.9	14.3	14.0	13.5	14.6	16.3	13.8	13.0	17.3	18.3
Ho	5.9	6.8	6.5	6.4	6.7	6.7	7.1	4.4	4.8	7.5	6.8	6.5	5.1	5.0	4.3	4.3	3.9	5.2	6.0	5.4
Ma	26.4	27.5	26.1	22.0	18.6	18.1	17.8	20.3	16.3	16.6	17.9	15.9	14.6	16.9	18.3	14.7	15.3	16.9	15.1	16.1
Pu	10.7	8.8	9.0	8.8	9.2	7.7	7.2	7.2	8.4	7.1	6.6	6.6	5.3	6.0	7.8	7.5	6.2	7.5	6.5	10.1
Re	21.0	19.4	15.3	17.7	14.3	12.0	13.0	12.3	16.1	11.9	10.9	14.7	16.4	11.3	13.9	16.5	13.3	13.8	9.8	7.9
Sc	14.9	13.3	12.0	10.6	13.7	13.7	9.7	13.2	12.8	14.0	12.6	11.1	13.9	16.5	10.7	7.9	12.1	9.7	8.8	9.2
St	10.6	12.1	12.7	11.8	12.6	16.4	11.3	14.8	14.2	13.5	18.0	14.2	14.7	14.0	17.1	14.5	17.5	14.0	12.9	12.6
Means	15.5	15.1	13.6	12.9	12.7	12.6	11.5	12.3	12.3	12.1	12.5	11.9	12.0	11.9	12.4	11.7	11.7	11.4	10.9	11.4

TABLE 3

THE MEAN AMPLITUDES OF THE NATURAL SLEEP KNEE-JERK TRACINGS OF THE SEVEN SUBJECTS AT VARIOUS STAGES OF THE HUNDRED STIMULATIONS RECEIVED AT EACH EXPERIMENTAL PERIOD

Subject	Mean Amplitudes of Kick Tracings in Millimeters for Successive Groups of Five Stimulations																			
	1 to 5	6 to 10	11 to 15	16 to 20	21 to 25	26 to 30	31 to 35	36 to 40	41 to 45	46 to 50	51 to 55	56 to 60	61 to 65	66 to 70	71 to 75	76 to 80	81 to 85	86 to 90	91 to 95	96 to 100
Co	15.3	12.3	9.7	6.2	8.1	6.6	7.9	10.2	5.2	7.8	7.4	7.9	5.0	5.7	8.5	7.1	6.7	4.6	7.6	8.0
Ho	7.2	4.4	4.4	2.1	2.7	2.0	1.6	1.4	1.4	.7	1.2	2.4	1.3	.7	.7	1.3	1.2	.6	1.2	2.2
Ma	16.3	12.9	10.7	9.3	12.0	11.2	11.1	9.4	8.0	9.5	11.5	12.5	10.7	8.6	11.1	11.6	10.7	11.0	11.4	6.5
Pu	15.8	9.5	5.8	5.0	4.4	3.6	2.5	2.4	2.8	2.7	2.6	2.8	2.3	1.1	2.0	1.8	1.8	1.7	2.0	1.9
Re	11.5	5.4	5.0	4.0	4.5	3.9	4.7	3.5	3.3	3.5	4.6	3.7	3.7	3.2	3.4	3.9	2.0	2.2	3.1	4.3
Sc	23.8	17.5	10.2	7.7	3.0	3.2	6.1	5.8	6.5	3.4	3.4	.9	3.2	12.9	3.1	1.4	.6	.3	1.1	.5
St	7.4	7.3	2.7	4.7	2.8	4.9	3.1	1.2	2.9	1.1	1.3	2.8	2.0	3.7	1.4	.6	2.1	4.7	3.0	2.9
Means	13.9	9.9	6.9	5.6	5.3	5.1	5.3	4.8	4.3	4.1	4.6	4.7	4.0	5.1	4.3	4.0	3.6	3.6	4.2	3.8

of 100 patellar stimulations in each of the three states: waking, trance, and sleep. Table 4 shows in columns the means of all the kicks for each subject. From these there are obtained the means for all the kicks in each state for all the subjects. Each of these final means represent the central tendency of 4300 kicks and the table as a whole summarizes the amplitudes of responses to nearly thirteen thousand patellar stimulations. Throughout the table the patellar reflex in the trance is very similar to the patellar reflex in the waking state. The final trance mean is 12.5 and the waking mean is 12.4. The difference of .1 is .12 the $P.E._D$ which is .85. This extremely low ratio indicates that the difference is very probably due to chance. But, comparing these means separately with the mean obtained for the patellar reflex in sleep a totally different situation is found. The mean kick amplitude in sleep was 5.4. This differs from the waking mean by 7.0 with a $P.E._D$ of .72. The difference is 9.7 times the $P.E._D$ indicating that a statistically significant difference exists between these two conditions. In comparing sleep with the trance we find the difference between the means is 7.1 with a $P.E._D$ of .92. The difference in this case is 7.7 times the $P.E._D$, again indicating that a statistically significant difference exists between the two means. An examination of Table 4 reveals that some subjects have the trance mean higher than the waking mean and others have the waking mean higher than the trance mean but in all cases, without exception, the sleeping mean is lower than either the trance or waking mean.

The differentiation indicated by comparing the means of the three states is even more marked if it is noted that Fig. III shows the first few kicks, ostensibly in the sleeping state, were actually always in the waking state because at the beginning of the period the subject had not yet had time to fall asleep. Thus some really waking reactions were included in the means for sleep, tending to raise these means somewhat above their true value. Furthermore, several of the subjects reported merely being in a light sleep, only three consistently reporting having been in a sound sleep. On the other hand,

all of the subjects were in a fairly deep hypnosis. Differences that are 7 to 10 times the P.E.$_D$ under such conditions are very significant and indicate a genuine physiological differentiation.

FIG. III. Graph summarizing the results of Tables 1, 2, and 3. This graph illustrates the course of the patellar reflex over a period of about fifteen minutes in each of the three states.

Figure IV indicates the course of the percentage of positive responses to the auditory stimulus over a period of about fifteen minutes in each of the three states. A comparison

of this figure with the curves in Fig. III reveals the following differences between the two criteria over a period of time. There is no appreciable drop in the percentage of positive

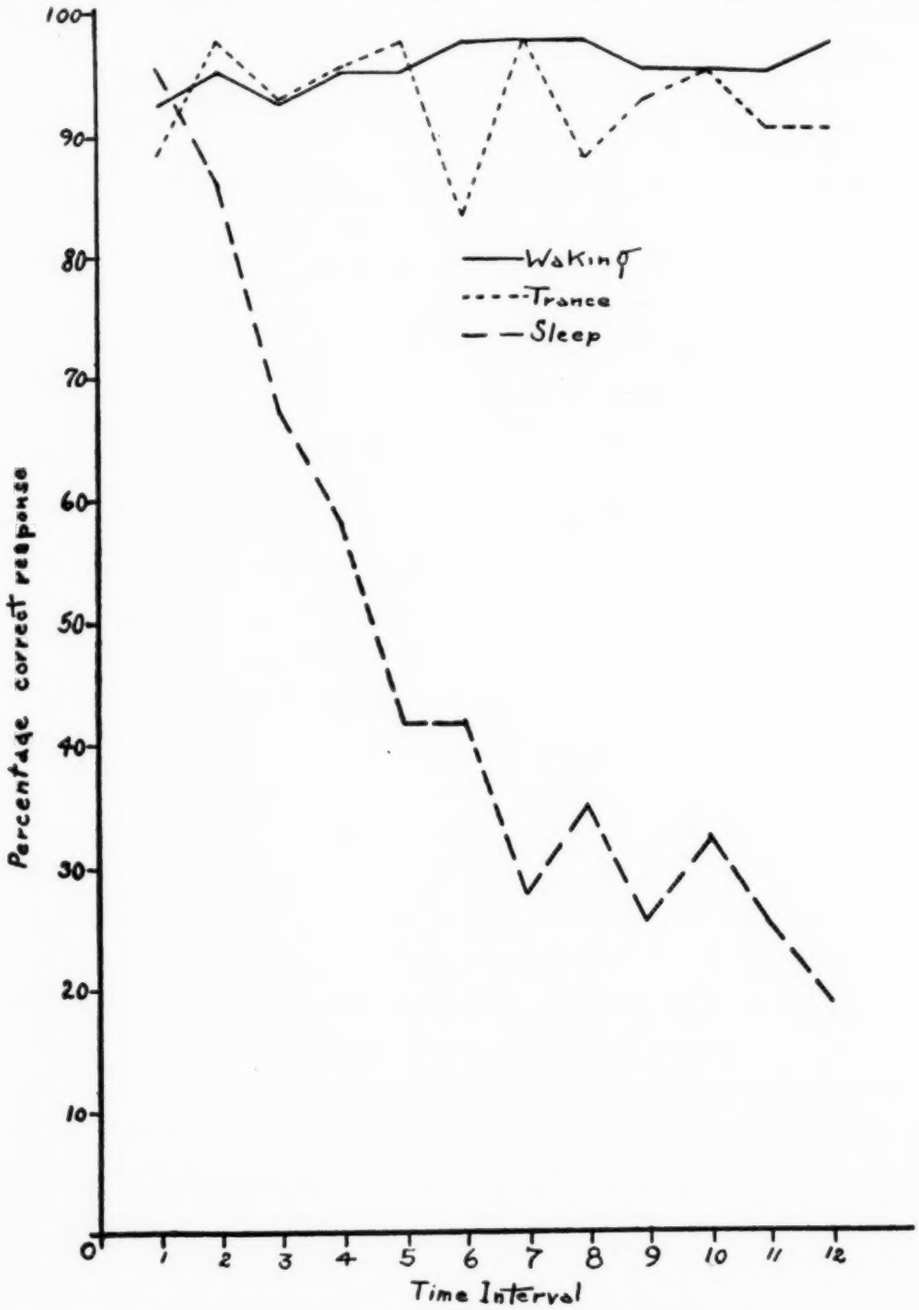

FIG. IV. Graph illustrating the changes in the percentage of positive responses to an auditory stimulus during a period of fifteen minutes in each of the three states.

responses in the waking and trance states corresponding to the drop in the amplitude of the patellar reflex as seen in

Fig. III. The percentage of positive responses in the trance seems to be on a slightly lower level than the percentage in the waking state. This difference is not shown in the results on the patellar reflex where, if anything, the patellar reflex is slightly higher in the trance. The sleep curve of Fig. IV shows a sharp initial drop similar to the corresponding drop in the curve for the patellar reflex in sleep, but the former does not flatten out as abruptly as the latter does.

TABLE 4

THIS TABLE SHOWS THE MEAN AMPLITUDE OF THE KICK TRACINGS IN MILLIMETERS AND THE PERCENTAGE OF POSITIVE RESPONSES TO THE BELL SIGNAL FOR EACH SUBJECT IN EACH STATE

Subject	Mean Amplitude of Kick Tracings			Percentage Positive Responses		
	Waking	Hypnotic Trance	Normal Sleep	Waking	Hypnotic Trance	Normal Sleep
Co.....	16.3	14.8	7.9	92	86	19
Ho.....	4.9	5.5	2.0	100	100	46
Ma.....	21.9	16.1	10.8	98	97	69
Pu.....	7.9	7.8	3.7	97	93	41
Re.....	12.4	13.5	4.3	97	98	69
Sc.....	11.0	12.0	6.1	89	87	54
St.....	12.6	18.0	3.1	96	96	51
Means.....	12.4	12.5	5.4	95.6	93.9	49.9
P.E.	1.31	1.05	.73	.90	1.32	4.08

The second section of Table 4 shows that the results of the voluntary response to the bell signal parallels the results on the patellar reflex. The table shows that the percentage of positive responses to the bell stimulus diminishes very greatly in sleep. The means in the second section of the table may be compared in the same way that the means in the first section were compared. The normal waking mean of 95.6 percent positive responses indicates the amount of error a subject in the normal waking state might make because of inattention. Contrasted with the trance mean of 93.9 percent it is found that there is a difference of 1.7 percent with a $P.E._D$ of .58. The difference is 2.9 times the $P.E._D$. This indicates the possibility of a weak tendency for the percentage of voluntary responses to diminish during

the trance. But, comparing the waking mean with the sleep mean, which is 49.9 percent, it is found that the difference is 45.7 percent with a P.E.$_D$ of 1.59. The difference in this case is 28.74 times the P.E.$_D$. The difference between the trance and sleep means is 44 percent with a P.E.$_D$ of 3.48. The difference here is also statistically very significant since it is 12.64 times the P.E.$_D$. These significant differences indicate a clear differentiation of both waking and the trance from sleep.

Conclusions and Comments

1. The patellar reflex shows no differentiation between the normal waking state and the hypnotic trance.

2. The voluntary response to an auditory stimulus shows what may be a slight tendency to be weaker in the trance than in the normal waking state.

3. Both the patellar reflex and the voluntary response to an auditory stimulus show a clear and distinct differentiation between the normal waking state and the normal sleeping state.

4. Both the patellar reflex and the voluntary response to an auditory stimulus show a clear and distinct differentiation between the hypnotic trance and the normal sleeping state.

These results make it quite clear that the hypnotic trance can not be considered as having any more than a superficial resemblance to sleep. Physiologically we may assume that the states are quite different. In hypnosis the subject is just as capable of carrying out a voluntary response as he is during the waking state. It is of importance to note that the response to a *normal waking* instruction was carried over into the trance without any suggestions to the subject in that state. It is difficult to come to any other conclusion than that sleep is not hypnosis and that hypnosis is neither a suggested sleep nor a modified sleep nor anything between sleep and the normal waking state.

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THE INFLUENCE OF FOUR DIFFERENT INTERPOLATED ACTIVITIES UPON RETENTION

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Problem and Method

The problem of the factors which condition degree of retroactive inhibition becomes increasingly important as the pervasive significance of the phenomenon itself is recognized. Inasmuch as living individuals can never escape the occurrence of progressively interpolated experience whereby each succeeding experience serves as interpolation to all preceding ones, the effects of such interpolation must be among the most ubiquitous phenomena of mental life. Peculiarly important to an understanding of retroaction is knowledge of how it occurs, whether in terms of perseveration, transfer or some other factor. The present paper is concerned with the question whether retroactive inhibition will occur, and in what amounts, when certain relatively intense non-learning activities, together with one learning activity, are introduced between learning and the measurement of retention. This question is suggested by Müller and Pilzecker [2] in the initial discussion of the phenomenon and of the perseveration theory. An answer to this question will establish some of the limiting conditions of an interpretation of the phenomenon.

Two separate experiments, productive of complementary results, have been performed. Each has been done by the customary retroactive inhibition technique. In Experiment I, 24 college girls went through each of four conditions twice in a counterbalanced order. Two conditions were gone through at each experimental sitting, the order per day being also counterbalanced. The learning material consisted of lists of nine nonsense syllables each, presented at a two-

[2] G. E. Müller and A. Pilzecker, Experimentelle Beiträge zur Lehre vom Gedächtniss, *Zsch. f. Psychol.*, 1900, Erg. Bd., 1, 1–300.

second rate on a hand-operated Chicago memory drum and learned by the anticipation method. By this method the first syllable in each list is the cue syllable and is not learned. The subject spelled, instead of pronouncing, the succeeding syllables. Timing was controlled by a small electric bulb set in a box open on the side toward the experimenter but invisible to the subject. The light, in circuit with a metronome, flashed briefly every two seconds, as a signal to the experimenter to expose the next syllable.

In each condition a list was given 10 successive repetitions and a record was kept of the subject's successes and failures throughout. An interval of five minutes, filled in four different ways, followed. At the end of five minutes the list was relearned or, if learning had not been completed in the original 10 exposures, learning was continued, until a criterion of three successive perfect trials had been reached. Description of the interpolated activities follows. (*A*) *Rest condition.* The subject read from *College Humor* under instruction to select and mark the best joke on each page. This activity was chosen as the standard or rest condition since it is sufficiently interesting to occupy the subject and to prevent rehearsal, without being very strenuous. It is, of course, far from being 'rest' in the sense of absence of definite mental activity, but an experiential vacuum is impossible of attainment and, moreover, one must choose some relatively mild non-learning activity to prevent rehearsal by subjects untrained in experimental precaution. (*B*) *Learning.* Immediately after the 10 presentations of the original list, 10 presentations of a second list of nine syllables were given under the same conditions. The remainder of the five minutes was filled by reading jokes as under the rest condition. After the relearning of the original list, this interpolated list was given one relearning presentation to prevent suspicion that it was not to be learned for retention. (*C*) *Tapping.* The subject tapped continuously with a metal stylus for four minutes and forty-five seconds under instructions to tap as rapidly as possible. An ordinary tapping board in circuit with an electric counter was used. The

counter was in full view of the subject, and knowledge of progress operated to keep the subject at a high rate of performance. A record of the total number of taps was kept. The fact that the average number per minute varies from 300 to 400, with most averages close to 400, is sufficient evidence that the subjects were intensely involved in the task. The experimenter's observation of their behavior supports this conclusion. (*D*) *Electric shock.* The subject read from *College Humor*, as under the rest condition, but during the five minutes 10 irregularly spaced electric shocks were given at the rate of two per minute. The shocks varied from 25 to 50 volts and were administered through electrodes attached to the wrists and connected through a rheostat with the house current. The voltage was varied somewhat to adjust to the initial reactions of the subjects. If, *e.g.*, an initial shock of 35 volts elicited a reaction, verbal or otherwise, indicative of great unpleasantness, the voltage was somewhat decreased; if the reaction was weak, the voltage was increased. The subjects were warned in advance that an electric shock might be expected at any time during the interval and that they were to read continuously without regard to the shocks.

In Experiment II certain changes in procedure were introduced. Whereas in Experiment I the lists had been constructed from syllables of mixed associative value, in this experiment only syllables of zero percent associative value were employed.[3] The original lists were given five, and the interpolated list under the learning condition ten, presentations. These two changes, together with the fact that but one cycle was gone through, will account for the lower degrees of learning and the poorer retention found in Experiment II. The rest condition was filled by reading poetry and selecting best lines, instead of by reading and selecting jokes. An electrically driven, instead of a hand-operated drum, was used. Save for these changes, conditions *A* and *B* were as in Experiment I. In condition *C* the subject tapped for four

[3] *Cf.* J. A. Glaze, The association value of nonsense syllables, *Ped. Sem. and J. Genet. Psychol.*, 1928, **35**, 255–267.

minutes.[4] In condition *D* continuous color naming was substituted for electric shock. The subject named colors for four minutes under instructions to name as rapidly as possible. The rapid rate of naming and the behavior of the subjects indicate that the instructions were carried out. Thirty-five college students, nearly equally distributed as to sex, went through each of the four conditions, at the rate of two per sitting, in an order which counterbalanced practice.

Results

Experiment I.—It is necessary, first of all, to ascertain whether the counterbalanced order has successfully cancelled differences due to practice and to differences between the lists. The treatment of the measurements of retention assumes equal degrees of learning under the four conditions and any marked departure from this assumption would invalidate the comparisons between the conditions. Degree of learning can be expressed with some completeness in terms of the number of correct anticipations, which are given for each cycle and for the whole experiment in Table I.

TABLE I

Mean Numbers of Correct Anticipations

	Conditions of Interpolation			
	Rest	Learning	Tapping	Shock
Cycle I	35.4	36.7	34.8	36.6
Cycle II	41.9	43.5	43.8	43.6
Total	38.6	40.1	39.3	40.1

The high degree of uniformity between the conditions renders valid the conclusion that any marked difference in retention must be an outcome of the interpolated conditions and not of differences in degree of learning of the original lists. The uniformity characterizes both cycles of the ex-

[4] In Experiment I the instructions for the interpolated activities were given before the experiment began. In Experiment II they immediately preceded the activity. Thus the tapping and shock conditions of the first experiment filled four minutes and forty-five seconds, while the tapping and color naming of the second experiment occupied but four minutes.

periment. A considerable practice effect occurs from the first to the second cycle, but within each cycle the agreement between conditions is high.

Retention has been measured in terms of recall, which is the number of correct anticipations at the first relearning trial; and in terms of trials to relearn. Relative retroactive inhibition is given by the quotient obtained by dividing the difference between the rest condition and each of the others by the score under the rest condition.

The data upon recall will be presented both by cycles and for the whole experiment. It will be seen from Table II,

TABLE II

MEAN RECALL SCORES AND RELATIVE RETROACTIVE INHIBITION

	N	Conditions of Interpolation						
		Rest	Learning		Tapping		Shock	
		Recall	Recall	R.I.	Recall	R.I.	Recall	R.I.
Cycle I.....	24	4.91	1.50	69.4	5.38	+09.5	4.83	01.6
Cycle II.....	24	5.50	1.41	74.3	5.45	00.9	5.00	09.1
Total.....	48	5.20	1.45	72.1	5.41	04.0	4.91	05.5
σDis.....		1.56	1.51		1.83		1.79	

which shows mean recall scores and relative retroactive inhibition, that wide differences appear between the conditions. (1) Interpolated learning uniformly produces a large percentage of retroactive inhibition, and much more than is yielded by any other condition. (2) In Cycle I interpolated tapping is followed by better recall than is rest, while in Cycle II the two conditions are practically equal. The sum of the two cycles shows a difference of .21 between rest and tapping in favor of the latter, but the sigma of this difference is $\pm$ .35. It may be concluded that tapping and reading jokes are virtually equal in their effects upon recall. (3) Interpolated shock produces in both cycles a small percentage of inhibition. The difference between the mean recalls under rest and shock is but .29 $\pm$ .34, however, which makes impossible any conclusion that shock has a definite inhibitory

effect. The agreement between the two cycles creates, perhaps, a slight presupposition in favor of such inhibition.

It should be added that the differences between recall after interpolated learning and after the other interpolations are trustworthy, the differences and their sigmas being as follows: Rest-Learning, $3.75 \pm .31$; Tapping-Learning, $3.96 \pm .34$; and Shock-Learning, $3.46 \pm .33$. The differences between the non-learning interpolations are of no significance statistically.

Essentially the same picture is presented by the retroactive inhibition computed from relearning scores [5] (Table III), save that here the interpolations of tapping and shock produce greater inhibition than in recall and interpolated

TABLE III

RELEARNING TRIALS AND RETROACTIVE INHIBITION

	Conditions of Interpolation						
	Rest	Learning		Tapping		Shock	
	Trials	Trials	R.I.	Trials	R.I.	Trials	R.I.
Cycle I	5.25	9.83	87.2	5.95	13.3	5.79	14.1
Cycle II	3.91	5.81	48.5	5.12	30.9	5.71	46.0
Total	4.58	7.83	70.9	5.54	20.9	5.75	25.5
σDis.	3.70	4.94		5.22		4.62	

learning produces slightly less. The difference between the mean relearning trials under the rest and learning conditions ($3.25 \pm .89$) is reliable, but the differences between rest and tapping ($.96 \pm .93$) and between rest and shock ($1.17 \pm .86$) are not. The percentages of inhibition under the tapping and shock conditions may be sufficiently large to indicate the likelihood of a tendency being present, especially in view of

[5] It is, of course, possible either to use the relearning scores directly or to compute saving scores from them. In this case the former have been used because in Experiment II saving scores would be negative throughout and relative retroaction computed from such quantities would be somewhat anomalous. If it is remembered that the raw relearning scores in the two experiments are not directly comparable on account of the differences in original learning, no confusion can result from their use. The implications of the results are clear regardless of the method used for the computation of percentages of inhibition.

the agreement between the two cycles. The differences between learning and tapping and between learning and shock are 2.29 ± 1.04 and 2.08 ± 1.00, respectively. Their magnitude and consistency support their reliability. It is of interest that, whether computed in terms of recall or of relearning, inhibition is greater under the tapping and shock conditions in the second cycle than in the first, although the unreliability of the differences involved prevents any certain conclusion here.

Experiment II.—Equality of learning between the four conditions of this experiment is shown by the mean number of anticipations under the conditions of rest, interpolated learning, tapping and color naming, which are: 13.02, 12.42, 13.45, and 12.77, respectively. The mean recall and relearning scores and the percentages of retroaction computed from them appear in Table IV.

TABLE IV

RECALL, RELEARNING AND RETROACTION

	Conditions of Interpolation			
	Rest	Learning	Tapping	Color Naming
Recall	4.00	1.05	4.05	3.91
σDis.	1.86	1.58	2.19	2.27
Trials to Rel.	6.57	9.48	6.82	7.05
σDis.	5.61	6.90	6.39	6.15
Recall R.I.		73.7	+01.2	02.3
Relearning R.I.		44.2	03.8	07.3

Recall after interpolated learning and tapping gives results which corroborate those of Experiment I in both amount and relation. Interpolated color naming produces no significant inhibition. The differences between the mean recall scores under rest, tapping and color naming are of no reliability statistically, but those between learning and each of the other conditions are reliable.[6] It is thus clear that the only significant inhibition is produced by the interpolated learning.

[6] The differences between recall after interpolated learning and after the other conditions are: Learning-Rest, 2.95 ± .413; Learning-Tapping, 3.00 ± .457; and Learning-Color Naming, 2.86 ± .468. The differences between recalls after the other conditions can be seen by inspection to be unreliable.

The relearning data corroborate those of Experiment I in relation, but differ from them in amount. Such differences are readily accounted for by the differences in the experimental conditions. The important fact is that the interpolated learning is the only condition which yields significant inhibition. On account of the great variability of the relearning trials none of the differences between the conditions is statistically reliable.[7] Since, however, the relations between the conditions are completely consistent with those found in Experiment I and with the data from the recall scores of both experiments, we may safely assume that they support a similar conclusion.

Discussion

The foregoing presentation of the experimental data has shown that in two experiments the interpolated learning of a second list of nonsense syllables is accompanied by a large amount of retroactive inhibition, while interpolated tapping is accompanied by very little, if any, when retention is measured by recall, and by small and statistically unreliable amounts when retention is measured in terms of relearning. When the subjects are given 10 irregularly spaced electric shocks while reading material comparable to that read during the rest interval, an insignificantly slight degree of inhibition in terms of recall follows. In terms of relearning the inhibition is larger but still unreliable. The same is true when continuous color naming is inserted between learning and recall. Almost no inhibition of recall and a statistically unreliable inhibition of relearning results.

The bearing of these results upon the two major theories of retroactive inhibition may now be considered. The two theories will be stated and the experimental results interpreted with regard to their implications for the theories. According to the perseveration theory, first enunciated by Müller and Pilzecker, memorizing tends to be followed by a gradually diminishing perseveration or continuation of excitation in the neural mechanisms involved in learning. This

[7] The largest difference, that of 2.91 between rest and learning, has a sigma of ± 1.51, for example.

amounts to an unconscious continuation of learning, or a ' setting-in ' of the neural connections. The immediate interpolation of any strenuous mental activity will interfere with this perseveration and will produce a poorer recall than would have followed a corresponding period of rest which would have enabled the perseveration to continue unhindered. It is the implication of the view of Müller and Pilzecker that retroactive inhibition varies with the intensity of the interpolated activity rather than with its similarity to the original material. This theory amounts to a statement that a material which has been less well learned than another material will be less well retained, with the additional statement that the locus of the difference between the retention values of the two materials lies, not in the overt experimental conditions under which the learning itself goes on, but in a hypothetical setting-in process, or continued learning, which is permitted to take place in one case and not in the other.

There are at least two ways in which this perseveration can be conceived. One is the hypothesis of Müller and Pilzecker, and the one usually meant when the perseveration theory is discussed, that it is a kind of continued neural activity or after-discharge. This could, presumably, be true on either a specific, reflex-arc view of brain functioning, or on a concept of generalized, patterned function. That neural perseveration is not in good repute in the field of neurophysiology need not now concern us. A second possibility is that there may be perseveration of muscular and organic ' sets ' which are prevented or dissipated by intense activity, or by that involving the whole organism, but which are relatively unaffected by mild activity. There may also be present in certain cases verbal perseveration of at least a fragmentary kind, but this is resolvable into the two possibilities described.

The other major theory is that of transfer. This theory, first applied to retroaction by DeCamp,[8] states that the elements of the interpolated activity either block or become

[8] J. E. DeCamp, A study of retroactive inhibition, *Psychol. Monog.*, 1915, **19**, no. 84, p. 69.

confused with those of the original material, thus diminishing the retention of the latter. This transfer may be conceived to occur in at least four ways. (1) DeCamp suggested that interpolated activity, involving either wholly or partially the same neural mechanisms as the original activity, would block the after-discharge of the latter and produce retroactive inhibition. Degree of retroactive inhibition would thus vary with degree of identity of neural elements. As usually interpreted, the activity blocked is a perseverative after-discharge, so that this type of transfer theory is classifiable also as a modified perseveration theory. (2) If, however, the inhibition resulting from elements identical to the two activities is conceived to be an outcome of confusion attendant on a new organization of the elements, with a weakening of the connections within the original list, it becomes a more strictly transfer theory. (3) A possibility offered by Webb [9] is that, without regard to neural processes, some of the elements of the original material transfer to the interpolated material, with a resulting weakening of the retention of the former on account of the partial dissociation of the elements from their original context. (4) Another possibility, also stated by Webb, assumes a transfer of items from the interpolated to the original material, without reference to neural processes. Such transfer might be either positive or negative. These two last theories are largely specifications of the second form of transfer theory listed.[10]

Inasmuch as nothing is known about the neural elements involved in the learning of any of the materials used in experiments upon retroactive inhibition, we shall consider only the type of transfer implied in the three last theories. Inhibition might, of course, also occur in terms of partially identical peripheral movements or 'sets,' but speculation about the organismic locus of learning data is fruitless until we are certain of the data.

[9] L. W. Webb, Transfer of training and retroaction, *Psychol. Monog.*, 1917, **24**, no. 104, p. 90.

[10] A summary of theories of retroactive inhibition will be found in E. S. Robinson, Some factors determining the degree of retroactive inhibition, *Psychol. Monog.*, 1920, **28**, no. 128, p. 57.

An attempt to coördinate the theories and the results of the present experiment may now be made. The bearing of the present results upon the perseveration theory and particularly upon the expectation which follows from it that any intense activity introduced immediately after the original learning should produce retroactive inhibition will be discussed. The interpolations of tapping, shock and color naming in this experiment were designed to require an intensity of activity analogous to that required by the interpolated learning, while differing much more than it does from the original lists. These interpolations also involve the whole organism to at least an equal degree. If the implications of the Müller and Pilzecker work that the intensity of the activity, and not its similarity to the original material, is the important factor in the production of retroactive inhibition, the interpolation of tapping, shock and color naming should produce a degree of inhibition comparable to that produced by interpolated learning. Whether, on this theory, to expect exactly the same amounts from all of the interpolations cannot be said, since no measure of the intensities involved is feasible. Probably, however, no one will doubt that the three non-learning interpolations under discussion are much more intense than is the reading of jokes or of poetry in the rest conditions, and at the same time more dissimilar to the original lists, and that, therefore, they are adapted to a testing of the influence of the factor of intensity or degree of activity upon retroaction. The conditions under which they were employed were, moreover, arranged to accentuate their influence, if present, since tapping, shock and color naming filled more of the five-minute interval than did learning. Actually, however, neither tapping, shock nor color naming produces any statistically significant inhibition in recall. Each yields a greater percentage of inhibition in terms of relearning, but the differences are too small and unreliable to permit of any conclusion save that, if these interpolations yield inhibition, its amount is very small. The inference that intense activities produce inhibition by preventing perseveration, whether the perseveration is thwarted by drainage or by other processes, thus finds no support in these results.

It follows, likewise, that no prevention of the perseveration of peripheral sets or of verbal patterns is involved, since tapping and color naming, respectively, may be expected to break up such patterns, if they exist. It might seem that the slight amounts of retroaction appearing under the shock condition are suggestive of perseveration, or at least not of transfer, since the shock and rest conditions differ only in the occurrence of 10 electric shocks which have no observable similarity to nonsense syllables. Even granting more inhibition than was found, however, no perseveration theory would necessarily be indicated. The interpolated shock may easily be interpreted to produce an emotional interference such as is described in Harden's [11] recent work. Such shock might operate, for example, by producing a negative set toward the experiment and by reducing motivation, or by causing the subject to be recalling or thinking about the shock experience while he is under instruction to recall and relearn the original list, thus preventing maximum effort at the latter activities.

If it is granted that the three non-learning activities are more intense than reading jokes, even though considerably less than is learning, it is difficult to interpret the results in any way which at all favors perseveration. It is at least evident that retroaction, when it occurs, as in the case of the interpolated learning condition of this experiment, must occur at least in large part because of the presence of some other condition than a perseveration which is preventable by intense interpolated activities of the kinds used.

Positively, moreover, a transfer theory is favored. There can be little doubt that the learning of a second list of nonsense syllables is more similar, both in form and in whatever meaning may be present, to the learning of a first list than is tapping, reading plus shock, or color naming, and that the chief factor in common to these three is that of degree of activity. Since the interpolated syllables yield a much larger amount of inhibition than do the other interpolations, and

[11] L. M. Harden, The effect of emotional reactions upon retention, *J. Gen. Psychol.*, 1930, 3, 197–220.

since other conditions than similarity do not favor a greater inhibition from the syllables, an explanation in terms of similarity and transfer is indicated.

If the three activities, tapping, color naming, and shock, are rated with respect to their similarity to learning nonsense syllables, although such similarity is in each case admittedly slight, it is clear that color naming and shock plus reading are more similar to the original learning than is tapping.[12] The experiments agree in placing tapping lowest in amount of inhibition produced. The relationships involved are not sufficiently certain to have more than suggestive value, of course.

Summary

In two experiments designed to test the influence of the interpolation of relatively intense non-learning activities upon retention, four interpolations have been used: learning, tapping, reading plus shock, and color naming. In each case a rest condition, in which the five-minute interval was filled by reading either jokes or poetry, has been used as a standard. The following results appear.

1. In both experiments interpolated learning produces a high degree of retroactive inhibition in terms of both recall and relearning.

2. In both experiments, likewise, interpolated tapping produces no significant inhibition in terms of either measure of retention, although relearning consistently yields more inhibition than does recall.

3. In one experiment each, interpolated shock and interpolated color naming are followed by no reliable retroaction. In terms of recall the two conditions are practically equal to the rest condition. In terms of saving, 25.5 and 7.3 percent, respectively, of retroactive inhibition appear, but the differences involved are not statistically reliable. It follows that verbal interpolations, relatively unlearned and relatively

[12] Color naming is the most overtly verbal of the three and involves a slight learning of verbal connections; the shock condition is accompanied by verbal activity although of the same kind as under rest; while the tapping is non-verbal and has no observable similarity to nonsense syllables.

dissimilar to the original materials, are insufficient to inhibit a learned series to any great extent.

4. The results are interpreted as unfavorable to the perseveration theory and in support of the transfer theory.

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SEX DIFFERENCES IN MOTOR SKILLS

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Early mental tests were composed of very simple operations, such as reaction time, color naming, and speed of tapping. Later opinion however seemed to be that performances of this nature were too simple to obtain meaningful differences between individuals which might relate to more complex intellectual traits. Still more recently, due possibly to the analytic approach of behaviorism and also to the widespread interest in reflexes and other physiological bases, there has been a return of interest to the more fundamental and underlying items of behavior. Along motor lines we can name a few of these. Muscio (**5**) and Perrin (**6**) engaged in general researches largely directed toward a study of the inter-correlations between motor abilities. Farnsworth, Seashore, and Tinker (**3**) studied the relations between simple and serial reactions together with mental test performances. R. H. Seashore (**8**) dealt with inter-correlations in performances by men on eight different tests. Others might be mentioned.

Previous research in motor skills has dealt largely with men alone, or has not been directed specifically toward the sex difference problem. This matter of sex differences in various types of performance has been a topic of ceaseless interest, both in speculation and in experimentation. Allen (**1, 2**) and Miles and Terman (**4**) have summarized recent literature on this topic from two different angles. Popular opinion on the subject varies in its expression of possible differences. Women are often conceded to be better in more delicate tasks, such as dancing, threading a needle, etc.; while on the other hand they appear unusually clumsy in athletic skills. Is this a matter of acquired skill, or is there some more fundamental basis?

In general, then, our problem is to study sex differences in motor ability. Are there any real, consistent, and reliable differences between the sexes in motor skills? More specifically, a few of the questions we shall attempt to answer are: (1) Are there differences in simple speed tests? (2) Do any different results come about when a certain element of strength is demanded? (3) What are the results when more delicate coördinations are substituted for speed tests? (4) Will training intensify or narrow down any sex differences that may exist in the beginning?

Previous Studies

There is little in the way of previous research which might cast light in advance on our topic. Perrin (**6**) and Seashore (**8**) both report inconclusive correlations between various tests of motor ability. Therefore, one should have a fairly comprehensive battery of tests in order to be sure that any differences found are reliable.

Allen (**1**) gives a thorough summary of recent literature on sex differences, including a section dealing with motor tests. To quote from him: "Motor learning has hitherto shown large sex differences, as in the Young slot maze, *e.g.* McGinnis agrees that boys from four to eight years of age are markedly superior in the 'man-and-show' maze, also that practice again favors the girls. This agrees with earlier studies which have found no sex differences in motor coordination, and with Goodenough and Brian who find girls gain more by practice in target shooting. McGeoch finds no large differences, in any of the literature. Husband and Miles find women sort cards faster, both for color and form. Ilyinsky gets a slow and unstable associative reflex in males, and a faster and more persistent one in females. Neubauer suggests that boys are a year ahead of girls in making mechanical toys that function well, and in adding technical details to their drawings. Interest factors are obviously present here." There seem to be two trends in this rapid summary: first, that sex differences are largely confined to performances of the mechanical problem type, and second, that even these differences are largely obliterated by practice.

While it is out of the scope of the present study, it might be remarked that there seem to be no real differences in the higher mental processes. Women, however, are usually thought of as more emotional, and some test results tend to confirm this hypothesis. Reliable differences along mental lines, then, probably lie in the direction of personality traits and interests.

Apparatus and Technique

The apparatus employed was the Seashore Motor Skills Unit, the following five tests being employed: Pursuit Rotor, Spool Packing, Serial Discrimeter, Crank Drill, and Speed of Tapping. The battery is completely described by Seashore (7), but we shall give a brief outline of the nature of each task for more immediate understanding. We made a few minor departures from the procedures Seashore recommends, but these changes concerned the length and number of trials, rather than the use of the apparatus.

(1) *Pursuit Rotor.*—This consists in following with a loose-hinged pointer a small target rotating near the periphery of a phonograph turntable. An automatic electric counter records contacts, perfect performance scoring 10 contacts each revolution. Twenty revolutions constitute a trial.

(2) *Spool Packing.*—Two spools are taken up at a time, one with each hand, and placed end to end in a tray; another pair is put just above these, and so on until the tray is filled with six pairs. The experimenter then slides the tray along, which dumps it, and automatically by this operation brings another tray into position, so that the subject may pack the next pair of spools without the slightest break in movement. Five trays full make up one trial, time being the score considered.

(3) *Serial Discrimeter.*—A number, 1 to 4, appears at a window; the subject presses the appropriate finger, which brings another number into view; pressing the correct key in turn moves this on and presents the next digit, and so on, until a revolution is completed, which involves 100 choice reactions.

(4) *Crank Drill.*—The number of revolutions done on a crank drill in 10 seconds was recorded by a Veeder counter.

(5) *Speed of Tapping.*—The number of taps on a telegraph key done in five seconds.

Subjects were undergraduate students in the University of Wisconsin, largely from the course in Experimental Psychology. A few more were gathered elsewhere to make up the total number of 30 men and 40 women.

Five trials in each test constituted one series. In the training program, five extra series were given to 10 subjects of each sex on the Pursuit Rotor and Spool Packing tests. These were given in series of five trials each, one such series on a day. The time of day or exact interval between successive tests was felt to make no difference in performances of this type, so no particular effort was made to keep these conditions strictly constant.

Results

A. Test Series

The figures for the five tests administered to the men (M) and the women (F) are given in Tables 1–5 below. The first two rows give the means for the respective groups; the third the difference divided by the standard error of the difference.

TABLE 1

Pursuit Rotor

Trial	1	2	3	4	5
Means.....M	17.6	22.5	30.6	32.3	38.0
F	11.9	16.5	19.8	26.2	23.8
Diff./σ diff.....	2.63 m	1.75 m	2.85 m	1.34 m	3.16 m

TABLE 2

Spool Packing

Trial	1	2	3	4	5
Means.....M	68.2	62.8	60.1	58.5	56.2
F	67.2	60.8	56.8	57.6	56.7
Diff./σ diff.....	.46 f	.88 f	1.80 f	.48 f	.27 m

TABLE 3

SERIAL DISCRIMETER

Trial	1	2	3	4	5
Means.....M	74.8	70.7	68.7	68.6	66.0
F	69.8	63.4	60.8	59.8	58.8
Diff./σ diff.....	1.88 f	2.52 f	4.06 f	3.67 f	3.10 f

TABLE 4

CRANK DRILL

	Means	Diff./σ Diff.
M.....	188.7	.80 m
F.....	185.2	

TABLE 5

SPEED OF TAPPING

	Means	Diff./σ Diff.
M.....	40.7	3.60 m
F.....	36.4	

The ratio of the difference between the means divided by the standard error of the difference indicates the reliability of any superiority which might be evident from comparison of the means. The small letter (*m* or *f*) after the ratio figure shows which group was superior. Kelley and other statisticians recommend a ratio of 3.00 or better before we pass a judgment of certainty, although 2.00 to 3.00 represents a fairly strong trend. Expressed in terms of probability 2.00 gives 98 chance, and 3.00 gives 100 (99.9+) chances in 100 that in a retesting the results would still be in favor of the group which made the better score at the time of the first test.

In comparing the various mean scores, it might be well to point out that a low score is desirable in the Serial Discrimeter and the Spool Packing tests, as the measure is time consumed in doing a constant amount of work, while on the other three tests a high score represents excellence of performance, since they involve work done within constant time limits.

The tests listed in Tables 1, 2, and 3 probably measure largely the same functions, serial action together with precise muscular coördination, although the Pursuit Rotor is more

continuous in nature than the other two, which are to some extent composed of series of discrete reactions. The Crank Drill undoubtedly involves strength to a greater extent than any other tests, while the Tapping test calls for a nervous-muscular tremor, and probably strength alone would be a handicap—certainly no advantage. On this basis we might expect a possible male superiority on the Crank Drill, female superiority on the speed of tapping performance, and rather uncertain differences on the three more complex tasks.

Actually, we find women are definitely superior over men in the Serial Discrimeter operation, while the men excel by nearly as much on the Pursuit Rotor. In both cases the differences tend to become larger with practice; and the results are highly reliable in the Serial Discrimeter, and nearly as good in the pursuit task. The consistent superiority of the females on the first named test and of the males on the latter in all five trials may be taken as evidence of reliability somewhat beyond that shown by each single figure quoted.

The Spool Packing test shows no real sex differences. We can see that in general women are about one second faster than men in completing their tasks, but since the standard deviations run in the neighborhood of 7 to 10 seconds, such a small difference as this is negligible. Even group prognosis is practically impossible, let alone individual prediction.

There is a reliable difference in favor of the men on the simpler speed of tapping test. However, there was no appreciable difference in the crank drill performance, contrary to expectation. In the Crank Drill tests, it was noticed that flexibility of the wrist produced better results than brute strength or hard effort poorly applied. A nervous tremor with very short arc enabled subjects to run up high scores on the tapping test.

Methods which produced the best results on the three complex tests might likewise be mentioned. In Spool Packing those subjects who most consistently kept the timing of the two hands together, and who placed the ends of the spools together before placing them within the tray were able to fill the five trays in the minimum of time.

Relaxation on the Serial Discrimeter seemed to be about the only definite clue as to advantageous procedure that could be ascertained. Several subjects remarked that they did better, and worked more smoothly when they were thinking of something else, attention to the task in hand being almost like a dream state. Certainly hard effort created only tension and confusion, and increased erroneous responses, which by the nature of the apparatus raised the time to complete the trial.

In the Pursuit Rotor a smooth circular motion was necessary to attain good results. This motion came principally from the shoulder, the arm being held fairly rigid. The result was a sort of flowing motion, with no jerky movements, even in corrections. It might be mentioned as a matter of interest that the men were especially fascinated by this, often requesting extra trials. The women were not quite so enthusiastic, although many showed considerable interest.

B. Training Series

Before discussing the training series proper, we might mention results on those tests in the original series on which some learning appeared. Of the three such, there were no valid differences in two of them, as to sex separation. In the Serial Discrimeter the men came down about nine seconds, while the women drop 10; in the Spool Packing test the gains are respectively 12 and 11 seconds. However, in the Pursuit Rotor the initial difference was about six contacts, while on the fifth trial it was over 14. Even here the ratios remained practically constant; each sex doubled its accuracy.

As mentioned previously, 10 subjects of each sex did five extra series of five trials each on two tests: the Pursuit Rotor and Spool Packing units. These seemed to give the best possibilities for improvement, or learning. We thought that possibly even if the native abilities of the two sexes should be largely alike, a protracted training period might disclose differences in ultimate capacity.

The results of this training series are given in Tables 6 and 7.

TABLE 6

TRAINING SERIES: SPOOL PACKING

Trial	1–5	6–10	11–15	16–20	21–25	26–30
Means.....M	55.7	51.0	49.2	48.2	47.2	44.7
F	56.8	53.6	49.7	47.8	46.4	46.2
Diff./σ diff.....	.45 m	.73 m	.18 m	.20 f	.38 f	.73 m

TABLE 7

TRAINING SERIES: PURSUIT ROTOR

Trial	1–5	6–10	11–15	16–20	21–25	26–30
Means.....M	34.1	88.9	128.4	134.0	137.8	141.4
F	23.0	71.5	93.1	120.5	134.3	139.7
Diff./σ diff.....	1.56 m	1.52 m	1.59 m	1.27 m	.36 m	.19 m

In general the results of this training program tend to show that, whatever there might have been initially, no consistent sex differences appear with learning. In fact on the Pursuit Rotor the original differences which were reliable are narrowed down to the point of disappearance by the thirtieth trial. This might possibly be explained by the fact that a point in learning has been reached where further improvement is rather difficult. The maximum score, 200, was never attained, but what appears to be a very slight and momentary in-coördination will materially lower the score. So while we have not encountered a true physiological limit, we may have a temporary plateau, which prevents the men from improving, while the women, who have not yet attained it, catch up. To check this hypothesis, one might use a smaller target, which would increase the difficulty of the task and would prevent subjects nearing the limit thus early in learning.

On the Spool Packing test there are no real differences at any time, which follows the trend shown in the initial performances of the subjects. Comparative variability scores show nothing of value in either case.

So in this training series we started out with one test showing rather reliable differences and the other none, and

we end up with both displaying practical equality of the sexes. Therefore, training neither intensifies nor maintains existent sex differences in motor skills, nor does it bring out any which were not apparent at first.

Summary

1. 30 men and 40 women were measured on five tests, three complex and two simple, of R. H. Seashore's Motor Skills Unit. Ten of each sex were given five extra series of trials as a training series on two of the complex tests.

2. On the complex tests women were better in one, men superior on a second, while the results on the third were equivocal. No particular types of operation on which one sex or the other might be consistently superior were suggested by our evidence. Men were definitely superior on one of the simple tests, but there were no reliable differences on the other.

3. The training series narrowed to practically nothing differences which were reliable at the beginning in one test, and left practically equal the comparative scores on the other.

4. All this evidence points in general to a practical equality of the two sexes in the motor abilities tested.

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THE MEASUREMENT OF FATIGUE BY PHYSIOLOGICAL METHODS[1]

BY F. A. MOSS, J. H. ROE, OSCAR B. HUNTER, LESLIE FRENCH AND THELMA HUNT

For years it has been recognized that fatigue is very largely a chemical phenomenon. Various qualitative tests have been devised as an indication of fatigue, but so far no satisfactory quantitative tests have been developed. It was with the hope of discovering some reliable quantitative test for fatigue that this study was undertaken.

Historical Background

Further back than we can find written records, certain physiological effects of fatigue have doubtless been noted. Such obvious manifestations of strenuous physical exercise as increased breathing, increased heart-beat, and increased perspiration could not fail to be noticed. The exercise, however, has to be rather strenuous for these metabolic and vascular changes to be observable without exact instrumental measurement. And our present purposes demand quantitative measurements and often the detection of changes produced under circumstances of rather mild exertion.

Physiological studies of the blood under various conditions led to the theory of fatigue as a condition produced essentially by an accumulation of fatigue products in the blood, such an explanation being credited by experiments demonstrating that a rested animal can be fatigued by injecting into its blood stream the blood from a fatigued animal. Fatigue is thus to be looked upon as a general bodily condition, as something which is transferred to various cells of the body, though it may be caused locally. As Hastings[2] says in

[1] The present investigation was undertaken under the auspices of the Society of Automotive Engineers. The study and tests have been possible through the cooperation of the George Washington University Department of Psychology and the Departments of Physiology, Biochemistry, and Pathology of the George Washington University Medical School.

[2] Hastings, Albert Baird, The physiology of fatigue.

writing on the physiology of fatigue: The physiologist must never "leave out of mind the fact that in some way or another, he is dealing with the whole organism, and not with one part alone."

Hastings, who has done considerable investigation of fatigue, views it as changed physio-chemical relationships in the body, and as a condition of reduced efficiency of energy transformations in the body. He stresses the importance of observation of the following in fatigue: The *muscles* as the primary seat of energy transformations; the *blood* as the vehicle of supplies and waste removal; the *cardiovascular system* as the distributing mechanism; the *respiratory, alimentary, and excretory systems* as a source of supply and means of waste removal; and the *endocrine glands and nervous system* as the coördinating and regulating mechanisms. Among the fatigue changes demonstrated by this investigator through experimentation with animals and human beings are the occurrence of hemolysis of red blood cells after severe exercise, the increased resistance of red blood cells to laking by hypotonic salt solution, change in carbon dioxide content of the blood, increased saturation of hemoglobin by oxygen, migration of chloride from blood cells to blood plasma indicative of a diminished osmotic pressure within the blood corpuscles.

Investigations by this same investigator and by him in conjunction with Scott[3] have shown that demonstrable changes occur also in the urine with fatigue. The investigation of changes in urine with fatigue by these men also has in its favor the fact that 12 variations in degree of fatigue, from rest (hospital cases) to running a twelve-mile marathon race, were used. Fatigue effects in their study were measured in terms of excretions in urine of sulphurs and phenols.

Investigations of blood sugar in fatigue should probably receive mention, though it is doubtful whether analysis of blood sugar content could be used as a practical measure of degree of fatigue. An investigation by Rakestraw[4] seems typical. "Short strenuous exercise invariably increased blood

[3] Scott and Hastings, Protein catabolism and fatigue.

[4] Rakestraw, N. W., Chemical factors in fatigue, Stanford Univ., 1921.

sugar concentration both in plasma and corpuscles, while a longer period of exercise was generally accompanied by a drop in blood sugar, which was greater in plasma than in whole blood."

The metabolism changes in fatigue have been extensively investigated by Hill [5] with a specially designed breathing apparatus which can be carried around during exercising. With this apparatus, he has measured the rate of consumption of oxygen and output of carbon dioxide under fatigue-producing conditions. Benedict [6] is also to be mentioned in connection with metabolism measurements following both physical and mental fatigue. This investigator has used great care both in his measurements of amount of fatigue in terms of mechanical units, and in his measurement of the metabolic changes.

Method of Present Study

The subjects used in the present study were 10 university men between the ages of 18 and 35. None of these at the time of the experiment were accustomed to strenuous exercise, nor regular systematic exercise of any degree of strenuousness. During the experimental period of three days all ate the same prescribed well-balanced diet, and took precautions to engage in no unusual activities during the period.

The method of producing fatigue consisted in riding a bicycle ergometer.[7] This is a machine originally used by Benedict and described by him as follows: "The rear wheel of a bicycle was replaced by a copper disk 40.5 centimeters in diameter and 6 millimeters thick. This disk is mounted in such a way that it rotates freely on a ball-bearing axle. A small sprocket wheel is attached to the axle and is in turn connected in the usual manner with the large pedal sprocket wheel by means of a sprocket chain. A wooden frame surrounds the periphery of the disk, and to the upper part of the frame is attached an electro-magnet. Binding posts are

[5] Hill, A. V., Muscular movement in man.

[6] Benedict, Francis G. and Carpenter, Thorne M., The influence of muscular and mental work on metabolism.

[7] The bicycle ergometer has been loaned by the Department of Agriculture.

attached to the magnet to connect with the electric cable leading to the observer's table, where strength of current can be regulated with great accuracy. The field of the magnet is so extended that the copper disk rotates in the center of the field with but a very small air gap between the surface of the disk and the surface of the magnet, and hence the resistance is wholly that of magnetic induction. A current of 1.25 amperes induces large eddy currents in the copper disk to such an extent that the resistance is very noticeable."[8]

By varying the strength of the magnetic field regulated through a rheostat and ammeter the amount of work performed in pedalling can be varied. The number of revolutions made is measured by an electric counter connected with the sprocket wheel. The ergometer has been calibrated in terms of calories, the work performed per revolution being .0231 when using a current of 1.25 amperes and 70 revolutions per minute, this being the speed and amperage used in the present experiment. On the third day of the experiment, each subject rode the bicycle for 15 minutes, steadily, at the rate indicated.

In the case of each subject, studies were made before and after fatigue of blood pressure, pulse, carbon dioxide combining power of blood, blood sugar, hemoglobin, blood counts, metabolism and respiration, urine (chemical and microscopic), and electrocardiograph records. On the first day of the experiment normal metabolism and respiratory tests were made and on the second day normal electrocardiograph records made. On the third day another normal reading for metabolism was taken and normal tests of all the other items made. The period of exercise followed these normal tests and immediately afterward the 'fatigue' tests were made. Each of the tests will be described in turn.

Results Obtained

1. *Blood Pressure.*—Arterial blood pressure was measured using an ordinary sphygmomanometer, by the 'auscultatory' method. Records were taken of systolic and diastolic pres-

[8] Benedict and Carpenter, The influence of muscular and mental work on metabolism.

sure and from these a study of pulse pressure has also been made. The blood pressure records obtained are shown in Tables 1, 2, and 3.

TABLE 1

BLOOD PRESSURE—SYSTOLIC

No.	Before Fatigue	After Fatigue	Difference
206	110	84	−26
207	120	98	−22
208	130	140	+10
209	118	124	+ 6
210	116	137	+21
211	116	132	+16
212	114	140	+26
213	104	130	+26
214	103	170	+67
215	114	160	+46

TABLE 2

BLOOD PRESSURE—DIASTOLIC

No.	Before Fatigue	After Fatigue	Difference
206	80	50	−30
207	80	58	−22
208	60	74	+14
209	80	50	−30
210	70	50	−20
211	72	60	−12
212	76	50	−26
213	76	52	−24
214	62	70	+ 8
215	78	62	−16

TABLE 3

PULSE PRESSURE

No.	Before Fatigue	After Fatigue	Difference
206	30	34	+ 4
207	40	40	0
208	70	66	− 4
209	38	74	+36
210	46	87	+41
211	44	72	+28
212	38	90	+52
213	28	78	+50
214	41	100	+59
215	36	98	+62

There is marked presence of increased systolic and decreased diastolic blood pressure after exercise. In all except two of the cases the systolic pressure is decidedly increased. The theory suggests itself that rather than being exceptions to the general tendency these two cases may represent different stages of fatigue from that portrayed in the other eight. This was indicated by observance of their reactions at the time of the experiment. At the end of the fifteen minute period they seemed to have reached a more profound state of exhaustion. With this in mind the blood pressure of five subjects undergoing the same exercise has been checked at one-minute intervals over a period of 20 minutes. In these, blood pressure readings fall into a curve showing rapid

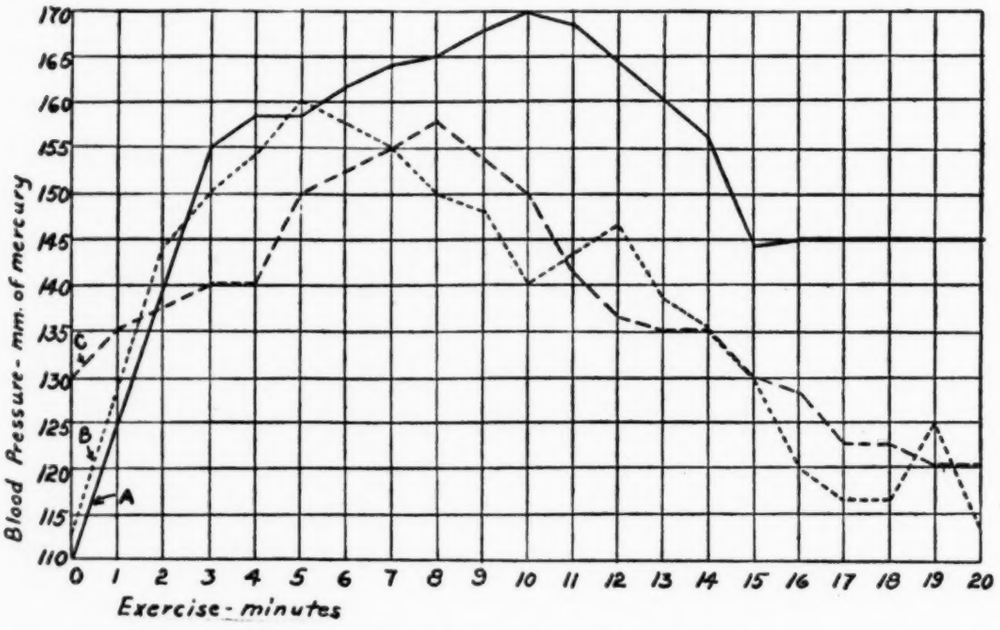

FIG. 1. Blood pressure curves for three subjects during 20 minutes severe exercise.

rise to a maximum height—then gradual fall. (See Fig. 1.) The more enduring subjects seem to show maximum height of the curve at a later period. Onset of exhaustion seems to follow the downward slope of the curve.

Closely related to blood pressure is pulse count. Every subject showed marked pulse increase. The lowest pulse rate recorded immediately after the exercise was 104, and this for a subject with an extremely slow normal pulse. The highest pulse rate recorded in the experiment was 180. The

10 subjects showed an average increase of 112.7 percent. (See Table 4.)

TABLE 4

PULSE COUNT

No.	Before Fatigue	After Fatigue	Difference
206	68	140	+ 72
207	68	160	+ 92
208	77	164	+ 87
209	76	154	+ 78
210	57	104	+ 47
211	80	180	+100
212	70	150	+ 80
213	70	156	+ 86
214	62	140	+ 78
215	72	148	+ 76

2. *Carbon Dioxide Combining Power of Blood Plasma.*—Under normal conditions the human blood contains a reserved supply of fixed alkalis or bases. It is this 'alkali reserve' which keeps the hydrogen ion concentration, or true reaction of the blood, slightly alkaline, close to pH 7.5. In processes of metabolism in the body there is a continuous production of excess of acid radicles, from such things as the combustion of carbon substances. During exercise there is a marked increase in these acid radicles, though in normal subjects they are not sufficient to change the reaction of the blood to acid. This condition, however, can be measured by the carbon dioxide combining power of the blood, which is lowered by depletion of the supply of fixed bases. Since the fixed bases of the blood constitute the chief means of transporting carbon dioxide from the tissues to the lungs depletion of the supply of fixed bases reduces the capacity of the blood to carry carbon dioxide. It is this decreased capacity which is shown in Table 5. The condition produced leads to an accumulation of carbon dioxide in the tissues and consequent blocking of the processes of oxidation, factors important in producing the condition of fatigue.

3. *Blood Sugar.*—Blood sugar records for the 10 subjects of the experiment are shown in Table 6. No consistent tendency in regard to blood sugar is found. The average

TABLE 5

CO_2 Combining Power

No.	Before Fatigue	After Fatigue	Difference
206	56	24	−32
207	56	33	−23
208	48	30	−18
209	50	25	−25
210	51	33	−18
211	42	20	−22
212	50	33	−17
213	49	28	−21
214	58	39	−19
215	49	29	−20

TABLE 6

Blood Sugar (Mgs.)

No.	Before Fatigue	After Fatigue	Difference
206	77	80	+ 3
207	73	80	+ 7
208	72	83	+11
209	64	87	+23
210	69	63	− 6
211	84	103	+19
212	69	64	− 5
213	72	90	+18
214	82	60	−22
215	72	95	+23

shows an increase of ten percent, but an examination of the records shows in three of the subjects a substantial decrease as compared with the normal control readings. The findings are in substantial agreement with the findings of other investigators. They may be compared with the statement already quoted from Rakestraw. The amount of an individual's blood sugar is increased in the initial stages of fatigue or exercise. But a stage is soon reached in which the extra liberation of blood sugar is more than offset by the extra demand for it, and the amount of blood sugar begins to fall. Records of blood sugar can hardly be an index of fatigue, since equal exercise does not affect all equally, and since individual differences in blood sugar reactions are wide.

4. *Metabolism and Respiration.*—Metabolism changes in fatigue have been measured by a Sandborn Graphic Metab-

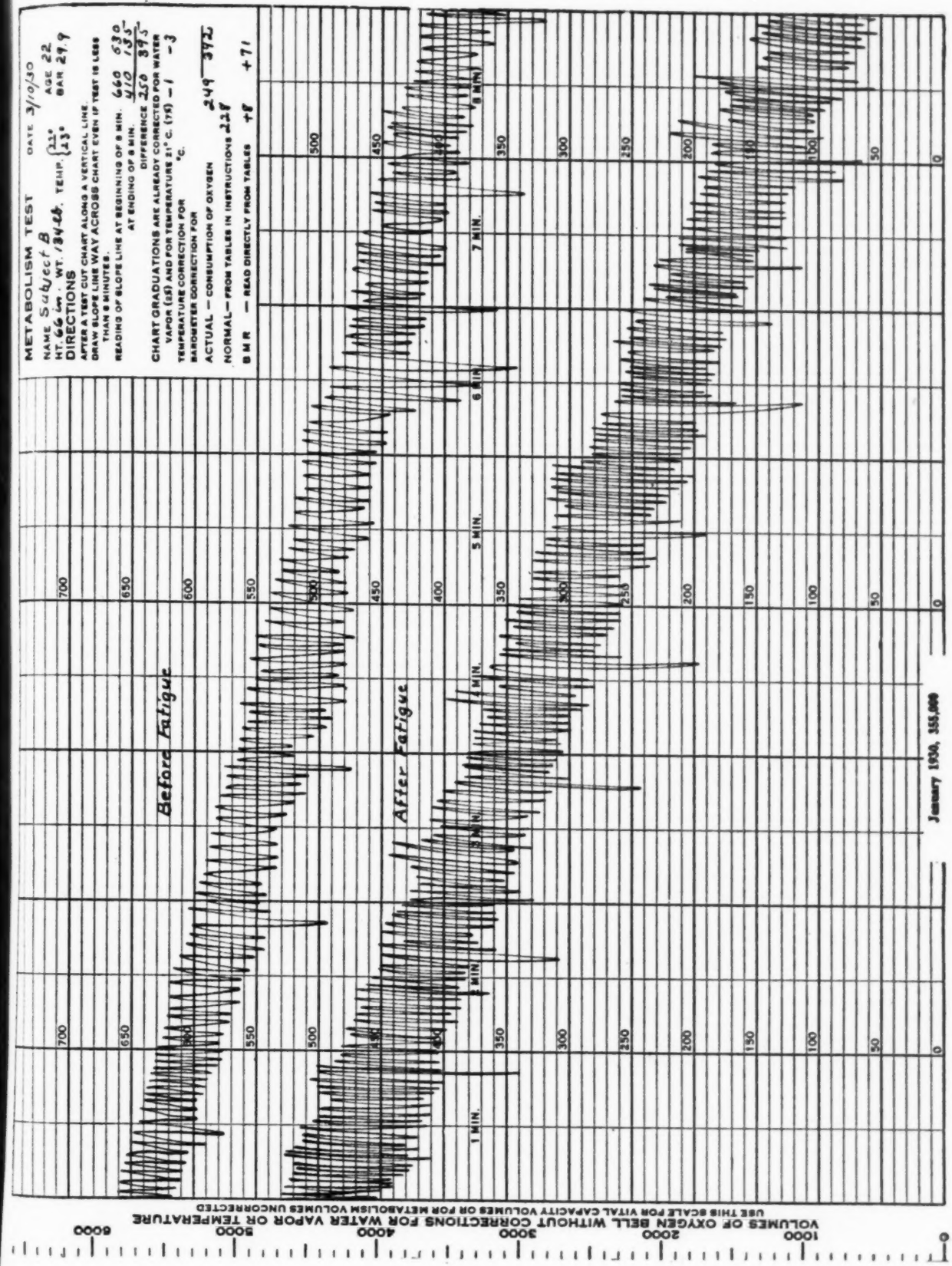
METABOLISM TEST
DATE 3/10/30
NAME Subject B
AGE 22
HT. 66 in. WT. 134 lb. TEMP. {23° / 13°
BAR 29.9
DIRECTIONS
AFTER A TEST CUT CHART ALONG A VERTICAL LINE
DRAW SLOPE LINE WAY ACROSS CHART EVEN IF TEST IS LESS THAN 6 MINUTES.
READING OF SLOPE LINE AT BEGINNING OF 6 MIN. 660 630
AT ENDING OF 6 MIN. 410 385
DIFFERENCE 250 245
CHART GRADUATIONS ARE ALREADY CORRECTED FOR WATER VAPOR (±5) AND FOR TEMPERATURE 21° C. (71) −1 −3
TEMPERATURE CORRECTION FOR °C.
BAROMETER CORRECTION FOR
ACTUAL — CONSUMPTION OF OXYGEN 249 245
NORMAL — FROM TABLES IN INSTRUCTIONS 238
B M R — READ DIRECTLY FROM TABLES +8 +7
Before Fatigue
After Fatigue
1 MIN.
2 MIN.
3 MIN.
4 MIN.
5 MIN.
6 MIN.
7 MIN.
8 MIN.
January 1930, 355,000
VOLUMES OF OXYGEN BELL WITHOUT CORRECTIONS FOR WATER VAPOR OR TEMPERATURE
USE THIS SCALE FOR VITAL CAPACITY VOLUMES OR FOR METABOLISM VOLUMES UNCORRECTED

FIG. 2. Metabolism records for one subject before and after severe exercise.

TABLE 7

BASAL METABOLIC RATE

No.	Before Fatigue	After Fatigue	Difference
206	+13	+54	+ 41
207	−17	+97	+114
208	+ 9	+71	+ 62
209	− 1	+94	+ 95
210	+ 4	+46	+ 42
211	− 3	+52	+ 55
212	+10	+26	+ 16
213	− 8	+35	+ 43
214	+ 1	+31	+ 30
215	− 2	+29	+ 31

TABLE 8

BLOOD COUNTS—BEFORE FATIGUE

No.	Hemoglobin	Erythrocytes	Leukocytes	Differential Count *				
				P	L	M	E	B
206	88	4,600,000	8,250	73	23	2	1	1
207	91	4,600,000	7,150	72	23	1	3	—
208	88	4,560,000	8,000	72	21	1	3	3
209	87	4,540,000	7,250	73	21	1	4	1
210	90	4,570,000	7,600	75	22	2	1	—
211	83	4,500,000	5,200	75	22	1	2	—
212	92	4,640,000	7,700	75	20	3	2	—
213	87	4,300,000	6,800	61	36	1	2	—
214	84	4,400,000	6,700	78	14	2	5	1
215	83	4,300,000	7,350	72	18	2	7	1
			BLOOD COUNTS—AFTER FATIGUE					
206	86	5,300,000	10,800	68	29	1	2	—
207	87	4,850,000	12,000	65	29	2	4	—
208	90	4,750,000	14,950	79	16	2	3	—
209	88	4,800,000	16,800	68	26	3	3	—
210	90	4,640,000	7,600	65	30	2	2	1
211	90	4,780,000	14,000	60	38	1	1	—
212	90	4,760,000	9,200	76	21	1	2	—
213	88	4,820,000	9,850	46	49	2	2	1
214	88	4,680,000	16,950	79	17	2	2	—
215	84	4,540,000	8,300	58	39	1	2	—

* P, Polymorphonuclear cells.
L, Lymphocytes.
M, Mononuclear cells.
E, Eosinophiles.
B, Basophiles.

olism machine. Metabolism rate or the rate of consumption of oxygen is greatly increased by exercise. The minute consumption of oxygen ranged from 185 to 249 cubic centimeters before exercise; and from 289 to 438 cubic centimeters after exercise. Measurements of 'Basal Metabolic Rate' show an average increase of 54.5 percent. Table 7 shows the results of the metabolism studies. Figure 2 shows a typical Sandborn tracing before and after fatigue, the change in slope of line indicating the change in metabolic rate.

5. *Blood Studies.*—Hemoglobin estimations and microscopic study of the blood are shown in Table 8. Fairly constant changes occurred in blood cell counts, both number of erythrocytes and number of leukocytes being increased after fatigue, the former an average of 6.4 percent and the latter 71.3 percent. The marked tendency to increased number of leukocytes no doubt represents a protective reaction on the part of the body to increasing accumulation of poisonous fatigue products. The leukocytosis is produced by an increase in percentage of lymphocytes at the expense of the polymorphonuclear cells, as shown in the differential count in the table.

6. *Urinalysis.*—Table 9 shows the urinalysis made before and after fatigue. The most constant and significant finding seems to be the presence of casts, mainly hyaline and finely granular types, after exercise. An increased number of casts in the urine is a common finding after exercise in those who are relatively unaccustomed to the exercise. Hyaline and granular casts represent extraneous material which has hardened in the kidney tubules. A certain amount of such material is normally present in the kidney. Strenuous exercise, with the accompanying extra kidney function, serves to 'shake out,' as it were, numbers of these tube casts.

7. *Electrocardiograph Records.*—These are records of changes in electrical potential accompanying heart-beat. As excitation in the heart spreads from the auricles to the ventricles, successive areas take on a lowered potential as the wave advances, returning to their former potential as the wave passes beyond them. In man the changes are of suffi-

TABLE 9

URINALYSIS

Before Fatigue

No.	Color	Specific Gravity	Reaction	Albumen	Sugar	Acetone and Diacetic Acid	Casts	Red Cells	White Cells	Pus	Epithelial Cells	Crystals	Amorphus Material	Mucous
206	Amber	1012	Neutral	—	—	—	—	—	Occasional	—	Occasional, squamous	Calcium oxalate	Some urates	—
207	Amber	1020	Acid	—	—	—	—	—	Occasional	—	Occasional, squamous	—	Considerable	Occasional
208	Amber	1015	Acid	—	—	—	—	—	Occasional	—	Occasional, round and squamous	—	Few urates	—
209	Amber	1015	Acid	—	—	—	—	—	Occasional	—	Occasional, squamous	—	Few urates	—
210	Amber	1030	Acid	—	—	—	—	—	Few	—	Few, squamous	—	Urates	—
211	Amber	1010	Neutral	—	—	—	—	—	Occasional	—	Few, squamous Occasional, round	—	Small amt.	Occasional
212	Amber	1022	Neutral	—	—	—	—	—	Few	—	Few, squamous	—	Considerable urates	Few
213	Amber	1015	Neutral	—	—	—	—	—	Occasional	—	Few, squamous	—	—	—
214	Amber	1014	Neutral	—	—	—	—	—	Few	—	Few, squamous	Few, triple phosphate	Moderate amount	—
215	Amber	1012	Acid	—	—	—	—	—	Occasional	—	Occasional, squamous	—	—	—

After Fatigue

206	Amber	1016	Acid	Faint trace	—	—	Occasional, hyaline and finely granular	—	Occasional	—	Occasional, round and squamous	—	—	Occasional
207	Amber	1019	Acid	Trace	—	—	Few, hyaline Occasional, finely granular	—	Occasional	—	Occasional, round and squamous	—	—	Occasional
208	Amber	1023	Acid	—	—	—	+	—	Occasional	—	Few, squamous Occasional, round	—	—	Occasional
209	Amber	1015	Acid	Trace	—	—	Moderate, hyaline, finely granular	—	Occasional	—	Few, round and squamous Occ., caudate	—	—	Occasional
210	Amber	1025	Acid	—	—	—	+	—	Occasional	—	Many, round and squamous	—	—	Many
211	Yellow	1017	Acid	Heavy trace	—	—	Many, hyaline Few, finely granular	—	Few	—	Many, round and squamous	—	—	Many
212	Amber	1024	Acid	Trace	—	—	Occasional, hyaline, finely and coarsely granular	—	Occasional	—	Occasional, round and squamous	—	—	Occasional
213	Amber	1015	Acid	Faint trace	—	—	Many, hyaline and finely granular	—	Occasional	—	Few, squamous and round	—	—	Occasional
214	Amber	1022	Alkaline	Very faint trace	—	—	Many, hyaline	—	Few	—	Few, squamous and round	—	Some	Few
215	Amber	1013	Acid	Faint trace	—	—	Occasional, hyaline and finely granular	—	Occasional	—	Occasional, round and squamous	—	—	Occasional

cient magnitude to affect the potential of the whole body, a fact taken advantage of in obtaining electrocardiograph records. In the present study the arrangement of electrodes commonly designed as Lead II has been used, one electrode being applied to the right arm and one to the left leg. These two leading-off electrodes were in circuit with a sensitive galvanometer, the movements of the galvanometer string being photographed on a moving film. Table 10 summarizes the electrocardiograph readings, showing the average magnitude of the various waves of excitation and the time elapsing between the various waves. It is somewhat difficult to indicate the exact relationship of the various waves to contractions in the auricle and ventricle. In general, auricular

TABLE 10

ELECTROCARDIOGRAPHIC STUDIES BEFORE AND AFTER FATIGUE

	Subject	P (Amp.)	P–Q (Time)	QRS (Amp.)		S–T (Time)	T (Amp.)	T–P (Time)	Rate
				+	−				
Before	206	2	1	7	8	1	3	7	76
After		3	1	10	11	1	6	4	100
Before	207	2	1	8	9	2	3	8	83
After		2	1	19	3	2	3	1	115
Before	208	1	2	13	7	2	3	10	71
After		3	2	16	6	0	4	2	108
Before	209	1.5	2.5	10	5	0	5	7.5	71
After		1.5	2.5	13	3	1	4	2.5	94
Before	210	Did not take tests							
After									
Before	211	2	2	15	3	2	3	13	56
After		1	2	6	3	2	2	0	83
Before	212	1.5	2.5	12	4	0	5	4	75
After		1.5	2	8	4	0	3	3	100
Before	213	1	3	15	5	1	5	12	71
After		2	1	26	3	1	3	1	107
Before	214	2	2	21	5	0	8	6	65
After		1.5	2	11	0	1	3	5	87
Before	215	1	2	10	0	1	1.5	8	62
After		3	2	13	0	1	3	2	100

contraction begins at the P-wave and finishes near the beginning of the QRS-wave. The sweep of excitation over the ventricles is represented by the QRS-wave; and the T-wave occurs at the latter part of the ventricular contraction, when blood is being expelled into the large arteries.

The electrocardiographic readings present very little of help in measurement of fatigue. About the only consistent result noted is the decrease in time between the T-wave and the P-wave, which simply indicates faster heart-beat, already shown by much simpler tests.

TABLE 11

SUMMARY OF CHANGES AFTER FATIGUE

(*In Terms of Percentage*)

Subject Number	Blood Pressure Systolic	Blood Pressure Diastolic	Pulse Pressure	Pulse Count	Metabolic Rate	CO_2 Combining Power of Blood	Blood Sugar	Respiratory Rate	Red Blood Cell Count	White Blood Cell Count	Polymorphonuclears in Blood	Lymphocytes in Blood
206	−23	−37	+ 13	+106	+ 36	−57	+ 4	− 73	+15	+ 28	− 7	+ 21
207	−18	−27	0	+135	+137	−41	+ 9	−325	+ 5	+ 68	− 9	+ 21
208	+ 8	+23	+ 5	+113	+ 58	−38	+15	− 55	+ 4	+ 87	+ 9	− 24
209	+ 5	−37	+ 62	+102	+ 96	−50	+36	− 83	+ 6	+131	− 7	+ 24
210	+18	−29	+ 89	+ 82	+ 40	−35	− 9	− 66	+ 2	0	−13	+ 37
211	+14	−17	+ 64	+125	+ 56	−52	+22	− 80	+ 6	+ 69	−29	+ 73
212	+23	−34	+137	+114	+ 15	−34	− 7	− 27	+ 2	+119	+ 1	+ 5
213	+25	−31	+178	+123	+ 46	−43	+25	− 33	+12	+ 45	−24	+ 36
214	+65	+13	+144	+122	+ 30	−33	−27	0	+ 6	+153	+ 1	+ 21
215	+40	−20	+172	+105	+ 31	−41	+32	− 45	+ 6	+ 13	−20	+116
	+	−	+	+	+	−	+	+	+	+	−	+
Average..	15.7	19.6	85.4	112.7	54.5	42.4	10.0	78.7	6.4	71.3	9.8	35.4
	+	−	+	+	+	−	+	+	+	+	−	+
Median...	20.5	28.0	77.0	113.5	43.0	41.0	12.0	60.5	6.0	57.0	8.0	22.5

Summary.—A summary of the changes with fatigue in terms of percentage of change from normal is presented in Table 11. The relative change shown in the various tests is also indicated in Fig. 3.

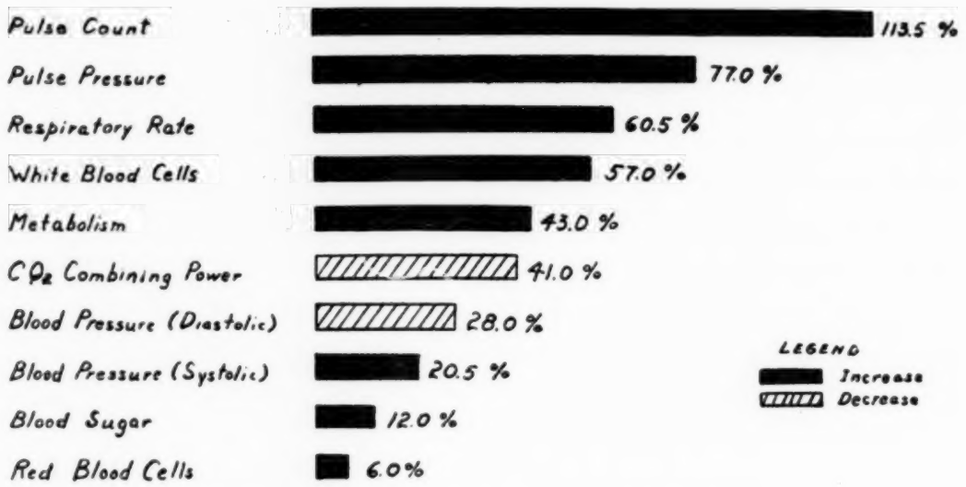

FIG. 3. Medians of physiological changes produced by marked muscular fatigue.

CONCLUSIONS

1. The present investigation bears out the theory that fatigue is largely a phenomenon of changed physico-chemical relationships.

2. Blood pressure records during severe exercise fall into fairly definite 'fatigue curves,' the degree of fatigue being indicated by the position of the blood pressure on the curve.

3. Measurement of the carbon dioxide combining power of the blood, and measurement of metabolism seem to offer reliable quantitative measures of fatigue.

4. Severe muscular fatigue is fairly constantly accompanied by increased blood cell counts, particularly white blood cell counts.

(Manuscript received July 14, 1930)

ERRORS OF MEASUREMENT IN A TEST AND A RETEST

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In order to compensate for the effect of errors of measurement in a correlation between initial score and gain (the effect being to depress the correlation from + 1 towards − 1) Thorndike and Thompson [1] have evolved the following formula (Thompson Formula 11): [2]

$$r_{ag} = \frac{r_{xy}\frac{\sigma_x}{\sigma_y}(1 - r_x)}{\frac{1}{\sigma_y}\sqrt{r_x\{\sigma_y^2 - \sigma_x^2(1 - r_x) - \sigma_z^2(1 - r_z)\}}}.$$

In the formula the symbols are as follows:

a = true initial value,
g = true gain,
$a + g$ = true final value,
e = error of measurement in initial value,
e' = error of measurement in final value,
x = measured initial value,
y = measured gain,
z = measured final value ($x + y = z$),
$x = a + e$,
$z = a + g + e'$,
$y = g + e' - e$,
r_x = reliability coefficient of x,
r_z = reliability coefficient of z.

The final correction formula as given (Number 11) was evolved from the so-called difference formula for the coeffi-

[1] *J. Exper. Psychol.*, 1924, 7, Thorndike, E. L., p. 225; Thompson, G., p. 321.

[2] The writer is indebted to Dr. Marguerite Lehr of the Mathematics Department of Bryn Mawr College for a discussion of the formula in connection with the present data.

cient of correlation which in the particular case is (Thompson Formula Number 3):

$$r_{ag} = \frac{\sigma_a^2\sigma_g^2 - \sigma_{(a-g)}^2}{2\sigma_a\sigma_g}.$$

The writer had occasion to attempt to correct a correlation of initial score with gain in the case of a vocabulary test given before and after a period of reading.[3] The test words represented the 'hard' words of the reading passages. For the special purposes of the experiment the same vocabulary test was used for the original test and the retest. Two tests were given to fifth and sixth grades, two tests to seventh and eighth grades, and a fifth test was given to both the fifth and sixth and the seventh and eighth grade groups. The tests were partly in 'same-opposite' form and partly in multiple choice form.

In an endeavor to discover whether the limited extent of the tests penalized those who scored high initially by not providing them with much opportunity within the test to improve their score, the correlation between improvement and possible improvement was calculated. This is the same correlation with signs changed as that between initial score and improvement. The correlations which were obtained (stated in terms of the correlation between initial score and gain) will be found in the r_{xy} column of Table I.

TABLE I

Test	N	r_{xy}	σ_x	σ_y	σ_z	r_x	r_z	r_x Corrected	r_z Corrected
5th & 6th grades									
U.....	375	−.36	5.74	4.73	6.04	.47	.549	.63	.708
S.....	375	−.218	8.88	5.56	9.73	.69	.71	.82	.83
L.....	375	−.16	9.01	4.73	9.49	.72	.73	.84	.84
7th & 8th grades									
U.....	301	−.21	5.41	3.85	5.43	.50	.45	.66	.62
T.....	301	−.217	10.76	6.60	11.68	.72	.797	.83	.885
P.....	301	−.236	11.23	5.99	11.65	.75	.795	.86	.88

[3] O'Shea, H. E., *A Study of the Effect of the Interest of a Passage on Learning Vocabulary*, Teachers College, Columbia University, 1930.

The remainder of Table I gives the data necessary for the solution of the Thorndike-Thompson correction formula. It will be noted that the reliability coefficients (r_x and r_z) are given as first obtained and also as corrected by the usual Brown formula.[4] The reliabilities were obtained by correlating the odd and even items for each test.

In five of the six cases the reliability of the retest (r_z)—the same test given again—is higher than the reliability of the initial giving of the test (r_x). Since errors of measurements shrink correlation coefficients toward zero, it may be that in some way the errors of measurement have been reduced in the second giving of the test, thus permitting the self correlation to assume a higher (more correct) value.

The solution of the formula resulted in an imaginary number in the denominator in all six cases, using the raw reliabilities, and in three of the six cases using the corrected reliabilities. The two sets of r_{ag} are given in Table II.

TABLE II

Test	r_{ag}	r_{ag} (Corrected Reliabilities)
5th & 6th grades		
U	$\frac{.57}{\sqrt{-1}}$	$\frac{.825}{\sqrt{-1}}$
S	$\frac{.397}{\sqrt{-1}}$	+.52
L	$\frac{.42}{\sqrt{-1}}$	$\frac{.36}{\sqrt{-1}}$
7th & 8th grades		
U	$\frac{.66}{\sqrt{-1}}$	$\frac{.50}{\sqrt{-1}}$
T	$\frac{.46}{\sqrt{-1}}$	+.145
P	$\frac{.33}{\sqrt{-1}}$	+.117

This particular outcome to the solution of the formula indicates immediately that the formula is somehow not applicable to the data of the experiment in question. The prob-

[4] Brown, W., *Essentials of Mental Measurement*, pp. 101–192, 1911.

$$r_n = \frac{nr_1}{1(n-1)r_1}.$$

able explanation lies in the underlying assumptions upon which the formula is built. They are the same assumptions which were used by Spearman in developing the correction for attenuation of a coefficient of correlation (the shrinking towards 0 of both positive and negative coefficients as a result of errors of measurement), namely, that errors of measurement in the test and in the retest have a zero correlation with each other and with the true initial value and with the true final value. It seems very likely that the conditions of this assumption are not met in the present case.

In the development of the formula, Thompson uses the following equations for substitution in his Formula 3:

$$\sigma_x^2 = \sigma_a^2 + \sigma_e^2 \text{ (Thompson 4)},$$
$$\sigma_y^2 = \sigma_g^2 + \sigma_e^2 + \sigma_{e'}^2 \text{ (Thompson 5)},$$
$$\sigma_{x-y}^2 = \sigma_{(a-g)}^2 + 4\sigma_e^2 + \sigma_{e'}^2 \text{ (Thompson 6)}.$$

The equations consider that all terms in:

r_{ae}	$r_{(a-g)e}$
$r_{ae'}$	$r_{(a-g)e}$
r_{ge}	$r_{ee'}$
$r_{ge'}$	

vanish, since these correlations are assumed to be zero.

The full form of each of these equations, which must be used if the correlations are not zero but are either positive or negative, is as follows:

$$\sigma_x^2 = \sigma_a^2 + \sigma_e^2 + 2r_{ae}\sigma_a\sigma_e,$$
$$\sigma_y^2 = \sigma_g^2 + \sigma_e^2 + \sigma_{e'}^2 - 2r_{ge}\sigma_g\sigma_e + 2r_{ge'}\sigma_g\sigma_e - 2r_{ee'}\sigma_e\sigma_{e'},$$
$$\sigma_{x-y}^2 = \sigma_{(a-g)}^2 + 4\sigma_e^2 + \sigma_{e'}^2 + 4r_{(a-g)e}\sigma_{(a-g)}\sigma_e - 2r_{(a-g)e'}\sigma_{(a-g)}\sigma_{e'} - 4r_{ee'}\sigma_e\sigma_{e'},$$
$$\sigma_z^2 = \sigma_a^2 + \sigma_g^2 + \sigma_{e'}^2 + 2r_{ag}\sigma_a\sigma_g + 2r_{ae'}\sigma_a\sigma_{e'} + 2r_{ge'}\sigma_g\sigma_{e'}.$$

At each point in the development of the final formula the same assumptions are utilized in order to construct formulae in terms of obtainable data.

It will be noted in Table II that three of the correlations become apparently correctible when the reliability coefficients are raised sufficiently high. The $\sqrt{-1}$ in the denomi-

nator of the solution of the formula results from

$$\sigma_y^2$$

being smaller than the sum

$$\sigma_x^2(1 - r_x) + \sigma_z^2(1 - r_z).$$

Consequently an increase in either or both of r_x and r_z may reduce the sum sufficiently to make it less than σ_y^2.

At first glance this would make it seem that the formula should be at once applicable to tests whose self-correlation is sufficiently high. However, it remains questionable whether in this case the real solution (as contrasted with the solution involving an imaginary number) can be accepted uncritically, inasmuch as the reliability coefficient appears in the formula under the usual assumptions in order to make σ_e and $\sigma_{e'}$ vanish from the formula.

Thompson's Formula 8:

$$r_{ag} = \frac{\sigma_x\sigma_y r_{xy} + \sigma_e^2}{\sqrt{\{(\sigma_x^2 - \sigma_e^2)(\sigma_y^2 - \sigma_{e'}^2 - \sigma_e^2)\}}}$$

loses σ_e and $\sigma_{e'}$ as follows:

Let

x_1 = an alternative measure of x,

e_1 = its error.

Then

$$r_x = \frac{\sigma_x^2\sigma_{x_1}^2 - \sigma_{x-x_1}^2}{2\sigma_x\sigma_x}.$$

Also

$$\sigma_x^2 = \sigma_a^2 + \sigma_e^2, \text{ since } x = a + e.$$
$$\sigma_{x_1}^2 = \sigma_a^2 + \sigma_{e_1}^2, \text{ since } x_1 = a + e_1.$$
$$\sigma_{x-x_1}^2 = \sigma_e^2 + \sigma_{e_1}^2, \text{ since } x - x_1 = e - e_1.$$

Therefore

$$r_x = \frac{\sigma_a^2}{\sigma_x\sigma_{x_1}} = \frac{\sigma_a^2}{\sigma_x^2} \text{ (Thompson Number 9)}$$

and

$$\left.\begin{aligned}\sigma_e^2 &= \sigma_x^2(1 - r_x)\\ \sigma_{e'}^2 &= \sigma_z^2(1 - r_z)\end{aligned}\right\} \text{ (Thompson Number 10).}$$

If the correlations amongst the errors and the true initial

score and true gain are not zero, then the following formulae would have to be used, the reliability coefficients could not stand alone in the formula, and consequently the transition to a real from an imaginary solution merely with rise in reliability could not be considered a dependable result:

$$\sigma_x^2 = \sigma_a^2 + \sigma_e^2 + 2r_{ae}\sigma_a\sigma_e,$$
$$\sigma_{x_1}^2 = \sigma_a^2 + \sigma_{e_1}^2 + 2r_{ae_1}\sigma_a\sigma_{e_1},$$
$$\sigma_{x-x_1}^2 = \sigma_e^2 + \sigma_{e_1}^2 - 2r_{ee_1}\sigma_e\sigma_{e_1}.$$

The σ_z^2 of the denominator of the formula, it will be remembered, was defined above as:

$$\sigma_z^2 = \sigma_a^2 + \sigma_g^2 + \sigma_{e'}^2 + 2r_{ag}\sigma_a\sigma_g + 2r_{ae'}\sigma_a\sigma_e + 2r_{ge'}\sigma_g\sigma_{e'}.$$

Even in the event that the terms in $r_{ae'}$ and $r_{ge'}$ vanish, there remains a term in r_{ag}.

$$2r_{ag}\sigma_a\sigma_g$$

which does not vanish. The correlation r_{ag} is the one which the whole formula is designed to solve. The appearance in one-half of the equation of a term involving the exact statement of the other half of the equation should be investigated for its feasibility.

It seems probable in the given situation, in which exactly the same test has been retaken, that there is some kind of a correlation between the errors of measurement, or between them and the true initial value or the true gain. It is conceivable that there might be a positive correlation between the errors of measurement in the first test and the errors of measurement in the second test. It is also conceivable that there might be a negative correlation between the errors of measurement and the true initial value or the true final value. What the correlation, if any, might be between the true gain and the errors of measurement in the measured initial value or in the measured final value is difficult to estimate.

Since the data in the present experiment seem to show that the basic assumptions of the correction formula have not been met and that, therefore, the formula cannot be used, it undoubtedly means that even in cases where a real

solution to the formula can be achieved experimenters should be cautious about assuming that the conditions of the formula have been met. In other words, the factors in the situation should be carefully examined to ascertain whether there is any reason to suppose that the correlation between first and second errors of measurement or between them and the true initial score or the true gain is not zero.

Since errors of measurement do undoubtedly depress a correlation between initial score and gain towards -1 it is important that they somehow be allowed for in investigations of change of score (such as the effects of learning, and so on) and since at the same time there may be many cases in which the assumption of lack of correlation between errors of measurement is incorrect, it seems essential that an alternative method of controlling errors of measurement be developed for use when the Thorndike-Thompson formula is not applicable.

The unexpected discovery of the present case in which the correlations involving errors of measurement are probably not zero, in initial-score-and-gain correlations, may perhaps serve to indicate the need for careful scrutiny of whether correspondence exists between experimental conditions and statistical assumptions, such as those involving errors of measurement, in various frequently encountered situations.

If experiments can be devised which in some way throw into relief characteristics of errors of measurement, this will be a substantial assistance to statistical control of true values and measured values.

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A NEW DEVICE FOR SERIAL ORDER LEARNING

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The apparatus here described serves the following general functions: (*a*) It presents a finger-response ten-unit multiple-choice serial-order learning problem of sufficient complexity to challenge the abilities of college and graduate students. (*b*) It is an apparatus in which the problem presented may be varied from day to day in as many ways as the permutation of ten things taken ten at a time. (*c*) It is an apparatus in which the symbolic aids to learning may be varied in innumerable ways. (*d*) It presents an apparatus in which both the signal of success and of error is automatic (*i.e.* independent of the experimenter). (*e*) It is an apparatus in which the signal of correct response may be varied in many ways (*i.e.* varied sense organ, or, varied in spatial location with respect to the same sense organ). (*f*) The same is also true of the signal of incorrect response or error.

In the present experiment the successful response was indicated by a loud sound emanating from a box in front of the subject. The signal of incorrect response was varied with the experimental group: (*a*) With the Control group there was merely no response, or no sound. (*b*) With the Ankle group there was a sharp shock emanating from the smaller of two contacts on the right leg. (*c*) With the Finger group there was an electric shock emanating from the key touched.

The electric circuits involved in the apparatus are shown in Diagram 1. Their function may be outlined best in relation to the procedure of the present experiment:

The subject was seated in an ordinary chair at *A* before a table on which rested the keyboard *B*. The copper wristlet *C* (6.5″ × 1″ piece of .005″ 'hard brush copper') was fastened on the right wrist by means of a two-inch rubber band

doubled once and slipped over the small hooks soldered to the wristlet. The 'calflet' *D* (same size as above) was similarly attached to the calf of the bare leg with a three-inch rubber band. The 'anklet' *F* was attached in the same manner with a five-inch band on the flat surface of the right ankle midway between the tendon of the tibialis anticus

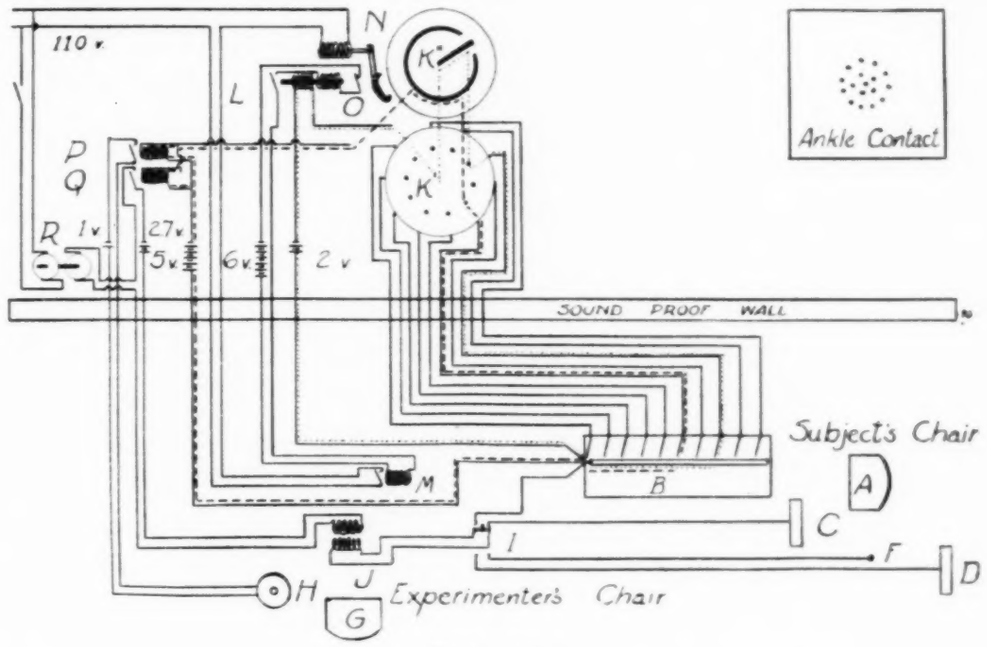


DIAGRAM 1

and the tendon of the peroneus longus, about six to eight inches from the floor. This 'anklet' consisted of 17 blunt steel points soldered in a circular piece of $\frac{1}{32}$" brass, $\frac{1}{2}$" in diameter. The pattern of these points is shown in the inset in the right hand corner of Diagram 1.

The experimenter seated himself at *G* with the head-phone *H* over his ear. He set the double-throw-knife-switch *I* so that the subject would receive the shock in the manner appropriate to the group that he was in. The experimenter then adjusted the induction coil *J* to the intensity appropriate to the locus of the shock. The intensities used had been determined by running a preliminary series of experiments. A shock of greater objective intensity was given to the Ankle group, but the subjective experience of the intensity was on the average almost equivalent to that of the Finger group.

After the subject had read the instructions he next di-

rected his attention to the keys on the keyboard *B*. The keyboard consisted of a 12″ × 7″ panel of ¼″ bakelite. On the left of the keyboard was fastened a brass strip (⅛″ × ⅝″ × 12″) milled on the inner side so that a sheet of paper might be slipped between it and a similar brass strip which was in the middle of the panel. The second strip, with a binding post attached on the end away from the subject, served as a common contact for all the keys. The keys were made of $\frac{1}{32}$″ copper (⅜″ × 3½″) and were bent up from the board so that they were normally $\frac{3}{32}$″ above the central brass strip. They were anchored to the bakelite by a screw and an inset binding post; the screw was set 2¼″ away from the free end.

If the subject was lucky and struck the 'correct key,' the 2 v. circuit indicated by the dotted line was completed through the rotary switch *K* and the 'self-holding' telephone relay was pulled shut. The 'holding' circuit which ran through the telephone relay was the 6 v. circuit that actuated the sound hammer *M*. As the sound hammer hit its base it served the double function of, first, telling the subject that the response was correct, and, second, of closing the 110 v. circuit through the solenoid *N*. The pull of the solenoid also accomplished two results: (*a*) it pulled the escapement-arm holding the escapement-wheel of the rotary switch and allowed the switch to rotate half a step; (*b*) as the escapement-arm completed its swing it opened the spring switch at *O*. Opening the switch at *O* broke the 6 v. circuit of the self-holding relay, this allowed the sound hammer to swing open and thus broke the 110 v. circuit. As the pull on the solenoid was released, a spring on the escapement-arm drew it back to its first position. This movement of the escapement-arm permitted the rotary switch to move the remaining half step forward, which 'set' it for the next correct response.

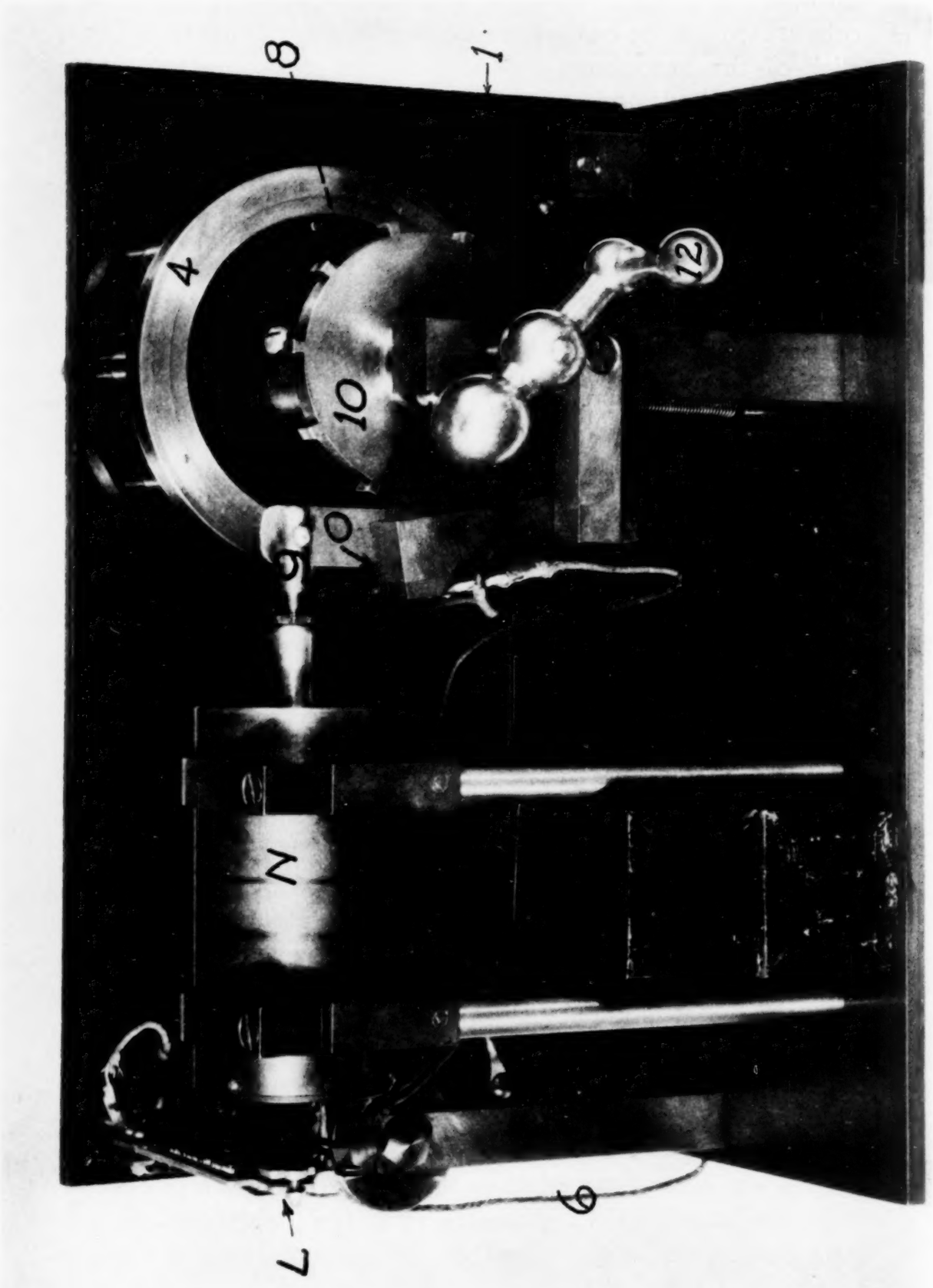
But, if the subject was not so fortunate, he struck one of the other nine keys and completed the 5 v. circuit shown by the line of dashes. This circuit actuated the telegraph relays *P* and *Q*. The relay *P* completed the 1.5 v. circuit

through the headphone *H* (a recording pen could easily be substituted for the headphone used in this experiment). The click of the headphone indicated to the experimenter that the subject had made an error. The relay *Q* completed the 2.7 v. (two cells of an Edison nickle plate sodium hydroxide storage battery) circuit through the motor driven interrupter *R* (which interrupted the current 720 times per second) and the primary circuit of the induction coil *J*. The induced current from the secondary circuit of the induction coil *J* passed to the double-throw-knife-switch *I*, and there its course varied with the experimental group to which the subject was allocated. If the subject was a member of the 'control' group, the switch *I* was left open. If the subject was a member of the 'finger' group, the switch was pushed 'up' and the circuit was completed through the central brass strip of the keyboard, through the key that was being held down, and through the subject's finger and hand to the wristlet *C*. If the subject was a member of the 'ankle' group, the switch *I* was pushed 'down' and the circuit was completed through the small contact *F*, and through the subject's leg to the 'calflet' *D*.

The principle and operation of the rotary switch shown in Plate I may be summarized in the following manner:

Ten metal points of equal height were equally spaced around the circumference of a circle on the (12″ × 6¾″ × ¼″) bakelite panel 1 which was anchored to the (12″ × 6″ × ¼″) brass base 2. A flat washer-like ring of metal (½″ width) of larger outer and smaller inner diameter was fastened to the inner surface of the circular bakelite plate 3 of 4½″ diameter whose axis of rotation was the center of the circle of metal points. At this stage we had a composite wheel which provided a continuous metallic contact with all ten points, regardless of whether the wheel was stationary or rotated.

A segment of a little less than two-tenths of the circumference was next removed from the metal ring and a bakelite inlay was substituted. A metal strip (⅜″ width) running from the center of the wheel to the circumference midway


8
1
4
12
10
9
N
7
6

between the two ends of the remaining segment of the ring was inlaid in the bakelite. Now, at this stage we had a wheel which, when stationary, provided continuous metallic contact around the circumference for nine of the keys while the tenth key was in contact with the center; when rotated, each metallic point was successively in contact with the center while the other nine were in contact with the remaining segment of the ring. This permitted one key to be the ' correct key ' while the other nine were ' errors.'

The addition of another washer-like ring 4 (½" width) to the outside of the bakelite wheel, but in continuous metallic contact with the inner ' eight-tenths ' segment, and a ' rider ' 5 to provide continuous stationary contact with the outer ring completed this part of the circuit which indirectly provided punishment for errors.

If we next added to this wheel some mechanism which would provide a rotation of one-tenth the circumference each time an electric circuit was completed through the strip which was in contact with the center and the circumference we would have essentially the rotary switch of the present experiment.

The mechanism which provided the rotation of the bakelite wheel is not clearly shown in the picture or diagram. The principle, however, was the same as that used in most watches and spring or gravity driven clocks in which the advancement of the mechanism is controlled by an escapement device. A constant rotational pull was provided by the four and one-half pound weight attached to the string 6 which ran over the pulley 7 to the spindle 8 (¾" diameter). Rotation resulted when the 110 v. solenoid *N* (5¾" above the base at the center) pulled the escapement-arm 9 and permitted the escapement wheel 10 to turn one-twentieth of a turn until caught by the lower pallet of the escapement arm. The escapement wheel used was 2¾" diameter inside the cogs; the cogs were $\frac{5}{32}$" in height. As previously pointed out, this swing of the escapement-arm resulted indirectly in releasing the pull of the solenoid by opening the spring contact switch *O*. When the pull on the solenoid was released the coil spring 11 pulled the escapement-arm back to its

original position and again permitted the escapement wheel to turn one-twentieth of a turn, and thus set it ready for a new advance.

The crank 12 was used in rewinding the string after a series of trials. In the present experiment twenty-three trials could be run before rewinding was necessary. The two condensers 13 were used to cut down the spark resulting from the closing of the 110 v. solenoid circuit. The self-holding relay *L* has previously been described.

On the rear of the bakelite panel were terminals to which the wires from the keys could be attached. Since these wires were of equal length the combination or series to be learned could be easily changed.

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